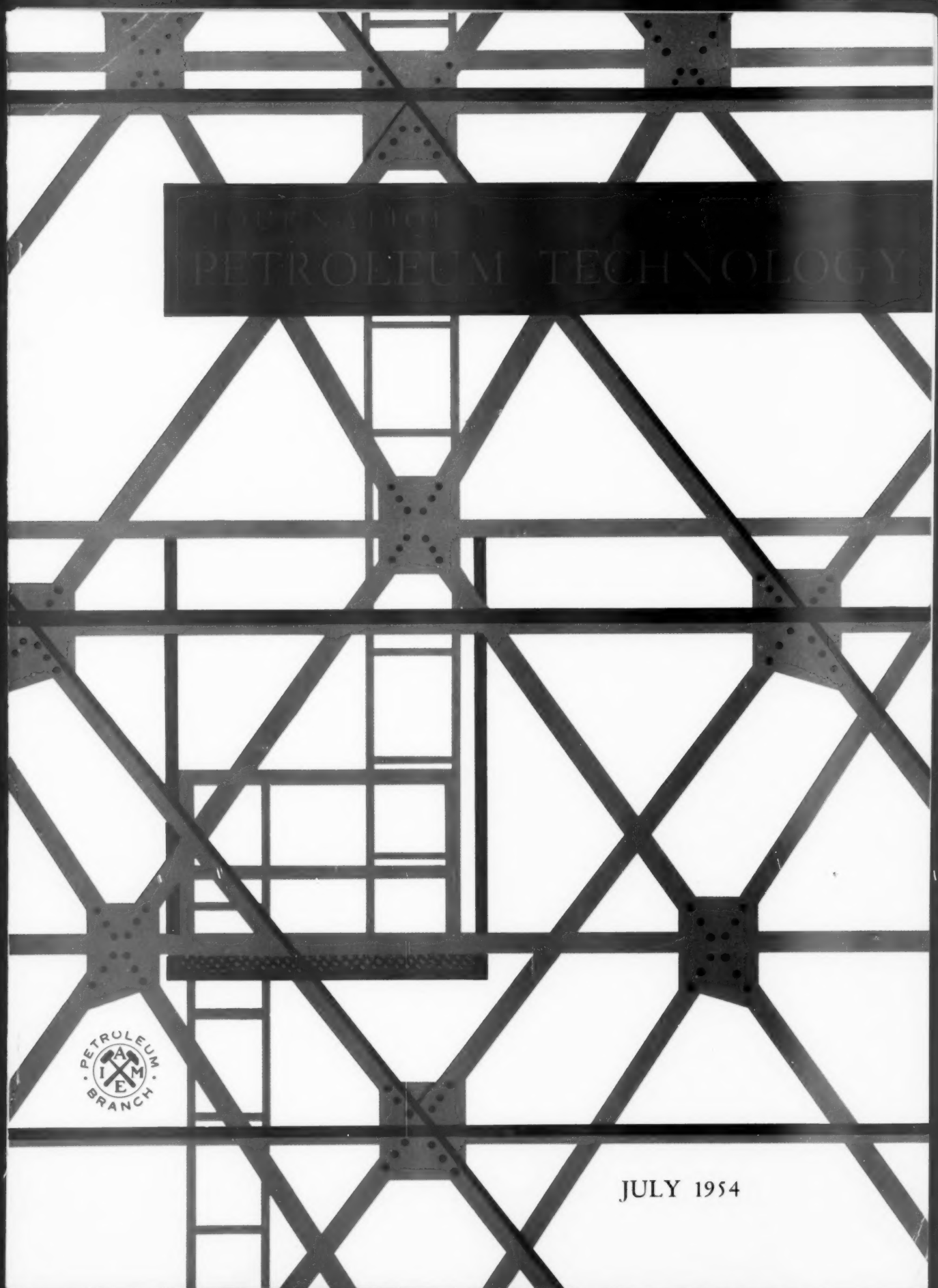
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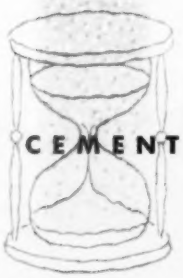

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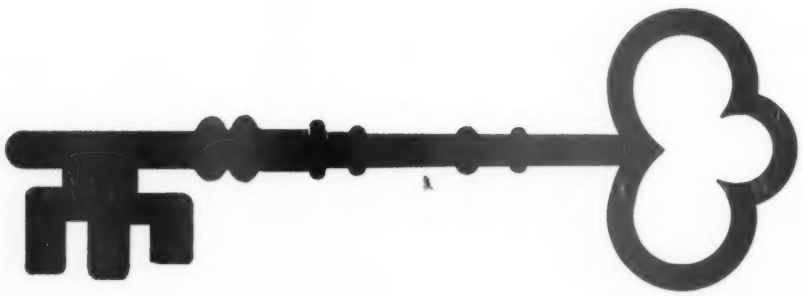

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On the Cover: An interesting design is created by this cross-section perspective view of a derrick.

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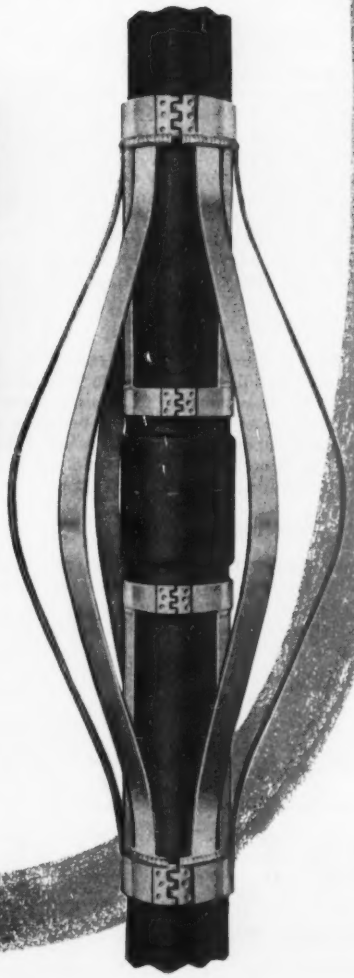

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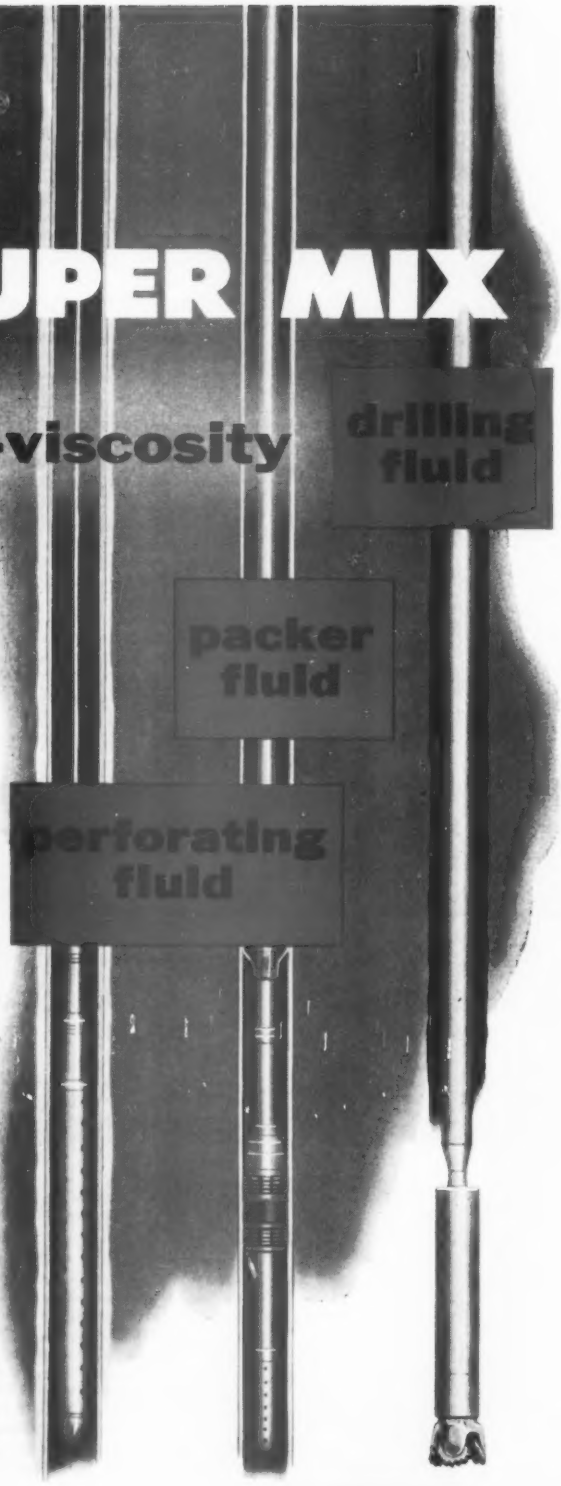

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*Effectiveness of Gun Perforating, Journ. Pet. Technology, January, 1954.

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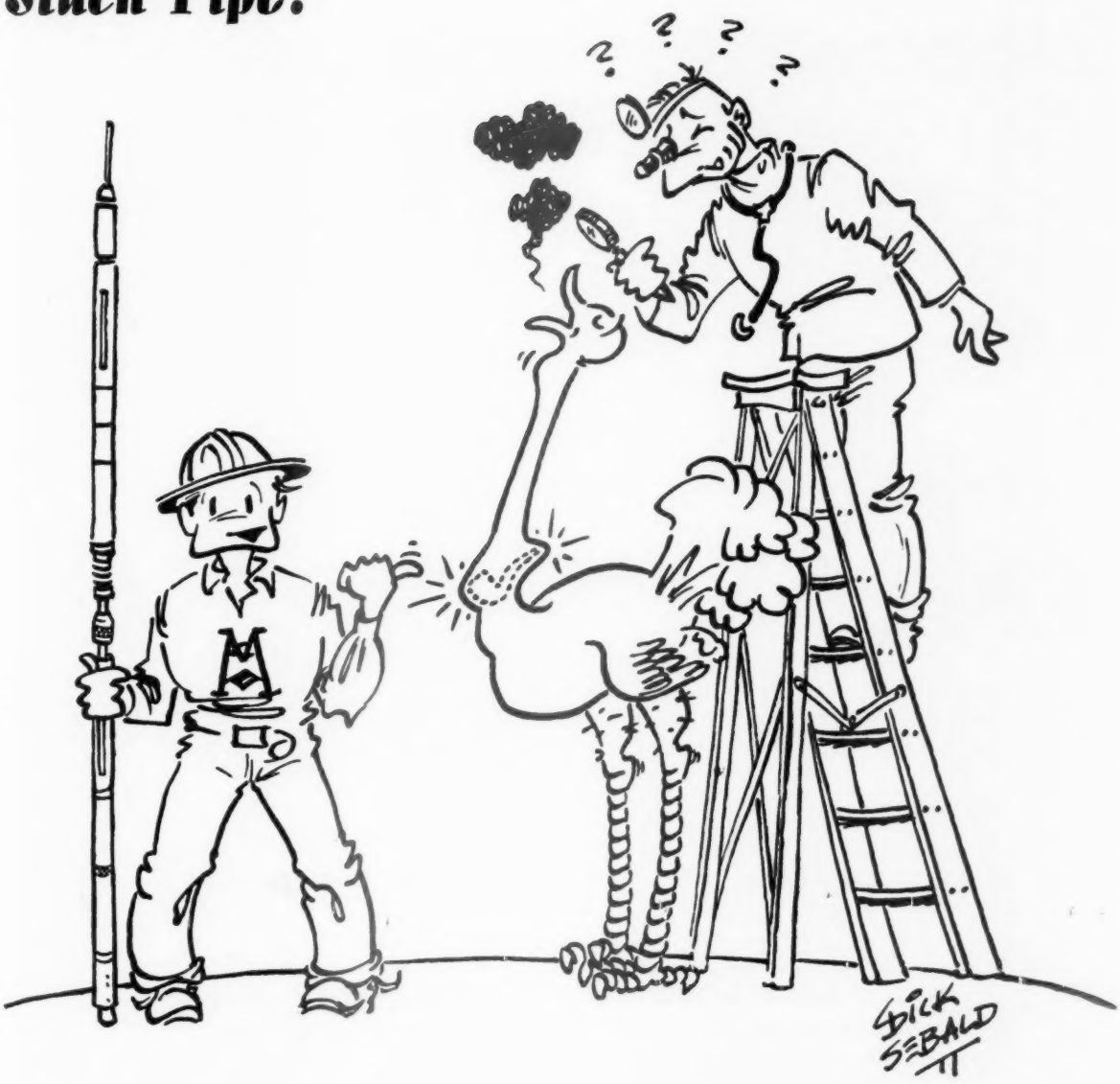

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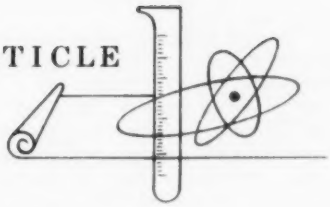


ALLOCATION of COSTS between PETROLEUM LIQUIDS and GASES

E. E. HUNTER

HUMBLE OIL & REFINING CO.
HOUSTON, TEX.

Introduction

Petroleum producers have been engaged for many years in supplying several different types of materials from the leases they operate. Some leases produce crude oil and casinghead gas, others produce gas-well gas and condensate, and still others produce all four of these materials. Therefore, the problem of allocating costs between these intermingled products is not a new one.

While in some fields gas has been the dominant product, most producers have been interested principally in oil. Consequently, little has been done about the cost allocation problem by oil producing companies. For accounting purposes, these companies have generally considered gas a by-product, and whatever realization was obtained from it was accounted for as a reduction of producing costs, which were all considered to be applicable to crude oil. The inadequacy of this procedure under present day conditions, and the need for a more realistic approach to the problem of accounting for costs, can probably be illustrated best by a brief review of the growing importance of gas in the economic structure of the industry.

Need for Allocation

Known natural gas reserves in the United States approximately doubled during the 10 years ending with 1952, rising to a total of nearly 200 trillion cu ft at the beginning of 1953. In terms of heat value the 200 trillion cu ft of gas is approximately equal to the combined heat content of the 28 billion bbls of crude oil and the 5 billion bbls of condensate in reserve at the beginning of 1953. However, the heat units produced in the form of oil in 1952 were almost twice as great as those produced in the form of gas — a good indication that there is much more room for expansion in production of gas than for crude oil.

The rapid growth in demand for gas since the end of World War II has brought about a substantial increase in the wellhead price, despite increasing reserves. In the Southwest, for instance, the price doubled in the period from 1943 to 1951, rising to an average of approximately 5.6 cents a thousand in the latter year. Marketed production of gas in the United States had increased to a rate of about 7.5 trillion cu ft in 1951 and over 8 trillion in 1952. The increase in demand thus indicated has been close to 12 per cent a year since 1946, more than twice as great as the rate of increase in demand for crude oil.

This extraordinary growth in the volume and value of gas has raised it to a position of importance that compels recognition, even by companies interested principally in oil production, of its status as a joint product. (For some companies and in some fields gas has for many years been a primary product.) Good accounting practice and business prudence dictate that oil producers now adopt some method of allocating costs to gas, or actually to all four of the joint products involved — crude oil, casinghead gas, gas-well gas, and condensate. However, full industry recognition of this fact has come so recently that no generally accepted method of making the allocating has been found.

Difficulties Involved

The difficulties involved in allocating costs between the various products supplied by petroleum producers arise from the fact that the intermingled products are so often produced at a cost that is common to all. Liquid and gases are lifted through the same well bore, by the same manpower, and under the same supervision. Under these circumstances costs cannot be traced *exactly* to each joint product.

This problem of allocating common costs is not peculiar to the petroleum producing industry. For example, the meat packing, milling, chemical, lumber, and petroleum refining industries all are faced with the problem of allocating common costs between two or more joint products. The difficulty or impossibility, of allocating such costs "exactly' by no means lessens the need for some careful estimates of the cost of each product for the purpose of measuring the relative profitability of various operations and as a general yardstick for testing the adequacy of sales prices. Each industry has developed cost accounting procedures that are logical under the prevailing operating circumstances. As conditions change, the accounting procedures change with them. There is no reason why petroleum producers cannot change their traditional custom of considering that all costs are applicable to crude oil, just as other industries have changed their customs when necessary.

Manuscript received in the Petroleum Branch office Oct. 19, 1953. Paper presented at the Petroleum Branch Fall Meeting in Dallas, Oct. 19-21, 1953.

A Method of Allocation

The discussion that follows will be devoted principally to the method of allocating producing cost that has been adopted by Humble Oil & Refining Co. In the search for a method that would take into account the peculiar characteristics of oil and gas producing operations and would provide reasonably accurate indications of relative costs, two methods of allocation were seriously considered. These can be termed the realization method and the energy content method. The energy content method is the one that was adopted, but the realization method will be discussed briefly first because it is familiar to so many people.

Disadvantages of Realization Method

The realization method of allocating costs assumes that costs are incurred in proportion to sales value. This method has a fundamental weakness. If the price of one product declines relative to others, its allocation of costs is reduced correspondingly, although there may be no change in the costs incident to the total operation or in the costs involved in handling the individual products. This is not so much a method of allocating costs as of allocating profit or loss according to sales values.

The realization method has the additional disadvantage of providing no indication as to what may be a realistic cost basis and, therefore, a minimum level of price for the various joint products, since it is keyed to what the product is selling for and makes no attempt to determine what it should be selling for to return a reasonable share of total costs. This method also differs in principle from the long established practice of determining certain unit costs of producing oil on the basis of barrels produced without regard to realization, even though the price may vary between grades of crude oil produced by the same operator from $2 to $3/bbl and sometimes even more in case of special high or low grades of crude.

Advantages of Energy Content Method

The energy content method, or principle, of allocating costs is based on the fact that the petroleum industry is engaged in supplying energy in the form of heat. The heat content of the liquid and gaseous fuels supplied is, to a large degree, the measure of the real value of the material. The energy content is, therefore, a good measure of the intrinsic value of the hydrocarbons being produced. It is reasonable to assume that the effort put forth to find and produce crude oil and gas, and the co-products of each, is in relation to the intrinsic value of each and should thus be divisible in relation to the energy content of each. Since the expenditure of money is usually very closely related to the effort put forth, it is reasonable to conclude that costs can be divided in the same manner as the effort when there is no more exact means of making the division. The unit of measure common to all forms of heat energy that can be used for the purpose of this allocation is the British Thermal Unit. A barrel of crude oil, like a barrel of fuel oil, has a heat value of approximately 6 million Btu's, while an Mcf of gas usually contains approximately 1 million Btu's.

The energy content method has the advantages of simplicity and stability, since the constant ratio of heat content can be used as the measure of energy produced.

One argument that may be presented against the allocation of costs on the basis of heat value is that realization for the various products may not be in line with their heat value, and that costs thus allocated may appear distorted in relation to the realization. This is simply arguing that the realization method is a better method of allocation, but the objection can be overcome to a large degree even if the realization method has merit. Gas-well gas at 15 cents/Mcf is delivered to industrial users on the Gulf Coast at a realization per Btu of only half that of fuel oil, its chief competitor, which is presently selling for about $1.85 a barrel; and gas at this price is even cheaper in relation to crude oil. However, since costs directly identifiable with the producing activity are substantially less per Btu for gas-well gas than for crude oil, because of the wide spacing of gas wells and the natural flow of the gas, the profit per heat unit should equal that of crude oil when the selling price of gas per heat unit is less than that of crude oil. Gas prices have advanced more rapidly in recent years than crude oil prices, and are continuing to move upward. Consequently, an allocation of costs between liquids and gas on the basis of heat content will in time appear more realistic relative to prices. In addition, it avoids the limitations and the constant changes involved in the use of the realization method.

Modification of Energy Content Method

The energy content method of allocation may be applied, if necessary, with modification designed to fit the peculiar circumstances of individual operators or particular situations. One of the major problems in connection with allocation of costs relates to casinghead gas. Such gas frequently brings a lower price than gas-well gas because its supply is regulated by the productivity of oil rather than by the needs of the customers, and because of other problems incident to the handling of casinghead gas. In such circumstances, the allocation of costs on a strict heat value basis may indicate a higher total cost for casinghead gas than can be realized from its sale. Nevertheless, if the oil is to be produced and casinghead gas must also be produced, an economic advantage will be gained from selling the casinghead gas if a price is received which more than covers the direct cost of handling the gas after it has come to the wellhead, even if it does not cover its full share of total cost.

It is generally recognized that casinghead gas may facilitate the production of oil by helping to bring it to the well bore and even to lift it to the wellhead. In view of this, any formula devised for allocation of producing costs may well allow casinghead gas some credit for the assistance it provides in lifting oil. Several means of determining the amount of such credit might be developed. In some cases operators may have gas repressuring projects in which they know the cost incurred in using gas to increase recovery of oil. Such costs might be considered as the credit to be given other casinghead gas produced with oil for its assistance in the oil production. Other operators may have both oil and gas operations of sufficient magnitude to determine the direct costs of handling gas from gas wells, and may then use such direct costs as representing those for the casinghead gas as well. This procedure also results in a credit to casinghead gas for its assistance in lifting oil, since it costs less to produce the same amount of energy from gas wells than from oil wells.

Application of Energy Content Method

Having decided on the basic principle of allocation to be used, the next problem is to apply the principle

to the costs that are related to production. Three general types of costs are involved. They are: direct producing cost, indirect producing cost, and exploration cost. Each of these presents its own peculiar problems.

Direct Costs

Direct costs include all costs that can be directly traced to the smallest unit used for accounting purposes, which is usually a lease. Examples of these costs are: depreciation, taxes, maintenance, fuel, pumping, reconditioning, etc. It can be seen that this category of producing cost requires allocation only to a limited extent. The cost of working over an oil well, for instance, could be attributed to the production of crude oil — *if* it were not for the fact that casinghead gas is also being produced from the well. Thus, the problem here is to find a way to allocate the cost between crude oil and casinghead gas; or the problem might be one of allocation between gas-well gas and condensate.

The method adopted for this purpose is basically the energy content method, with a modification that has already been described. Direct costs applicable to gas leases are first compiled and allocated between gas-well gas and condensate in proportion to the aggregate heat content of each. The unit cost thus obtained for gas-well gas is then applied to the volume of casinghead gas produced on oil leases, and the balance of direct costs compiled for oil leases is allocated to crude oil production. This assumes that it costs exactly as much per unit to produce casinghead gas as it does to produce gas-well gas.

Indirect Costs

Indirect costs, usually including division and home office supervision and staff expenses, present a somewhat different problem because they are not directly related to either oil wells or gas wells. Since these costs are closely related to direct costs they are allocated in proportion to the amount of direct costs allocated to each product. There is considerable precedent in accounting practice for this type of allocation.

Exploration Costs

Exploration costs usually include such items as dry hole costs, lease rentals, surrendered leases, test-well contributions, and all types of geologic, geophysics, and leasing costs. The allocation of exploration cost present a more difficult problem than the other two types of producing cost.

In one sense, exploration cost is related to the volume of hydrocarbons discovered rather than to the volume produced. However, the accounting concept of exploration cost is much the same as that of research and development costs. Many industries must, by their very nature, expend considerable sums in research activities in order to remain in a competitive position in relation to the other members within that industry. In this light, such cost must be viewed as a normal and recurring charge to current operations.

Obviously, the exploration effort of the petroleum industry must be conducted to provide the reserves that are necessary for a producing company to stay in business. For this reason, most companies have elected to expense exploration cost currently. Consistent with the energy content principle, this expense is allocated to the four joint products in proportion to the aggregate heat content of each.

Illustration of Allocation

The results of the allocation procedure just described can be illustrated by the following hypothetical example, which compares the traditional method of allocating all cost to crude oil with the energy content method of allocation:

		Crude Oil	Casing-head	Gas-well Gas	Con-densate
Vol. of production — 000's		1,000 Bbl	1,000 Mcf	1,000 Mcf	1 Bbl
Heat equivalent — 000's		1,000 Bbl	167 Bbl	167 Bbl	1 Bbl
		COST PER UNIT			
		Traditional Method	Allocated by Energy Content Method (approximate figures)		
	Total Cost $ 000	Crude Oil Per Bbl	Crude Oil Per Bbl	Casing-head Per Mcf	Gas-Well Per Mcf	Con-densate Per Bbl
Direct Cost-Gas Leases	$ 60	$1.00			$ .06	$ .36
Direct Cost-Oil Leases	940		$ .88	$ .06		
Indirect Cost	330	.33	.29	.02	.02	.12
Exploration Cost	500	.50	.37	.06+	.06+	.37
Total	$1,830	$1.83	$1.54	$ .14	$ .14	$ .85

It must be remembered that direct costs are accumulated for gas leases and for oil leases and that the allocation is made separately — hence the difference in cost per Btu and per barrel between crude oil and condensate. It must also be remembered that these figures are purely hypothetical.

Definition of Gas Production

One of the troublesome problems involved in the entire procedure of producing cost allocation is the definition of gas production for the purpose of computing the allocation factors. The fact that gas is often handled more than once before it is sold or used as fuel is the root of this problem. Spent gas lift gas, for instance, should not be included as production for the purpose of this allocation because to include it would have the effect of allocating more cost to gas, while it actually helps reduce the cost of lifting oil. The same thing is true of cycled gas and gas returned to the same reservoir for pressure maintenance. Flared gas would appear at first to be the type of production that should bear its fair share of the cost, but with conservation practices constantly tightening down on flaring of gas to the point where about the only gas that will be flared in the future is that which is not salable or usable under any circumstances, this first appearance might be misleading. If it is not a commercial product it should be considered as a waste product and no costs allocated to it, as such. Consequently, flared gas must be kept out of the production volume for the purpose of cost allocation. Stored gas, on the other hand, probably should be considered as production since the storage process is usually intended to be merely a postponement of sale. The stored gas will also have to bear its proper share of the cost when it is produced from the reservoir in which it is stored.

Limitations of Method

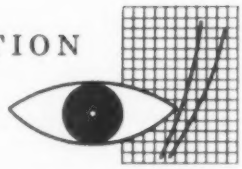
The method of allocation that has been described was designed to indicate average costs rather than costs for individual fields or leases. When applied on an over-all company basis, it appears to give results that are reasonable. When applied to smaller areas the results are more erratic, and the method may not always be satisfactory for the allocation of costs in a particular field or on a particular lease.

(Continued on Page 57)

REPORT and INTERPRETATION

JOE B. ALFORD

EXECUTIVE SECRETARY
PETROLEUM BRANCH, AIME



Recent Branch Executive Committee Actions

A summary of the important decisions made by the Petroleum Branch Executive Committee during its February and June, 1954, meetings are outlined below in this Report.

Petroleum Branch Fall Meetings

Registration Fees: The growth of the Branch Fall Meeting, from an attendance of 937 men at New Orleans in 1950 to an expected 2,000 in San Antonio next October, has increased almost everything in connection with the meeting. The number of papers on the program this year will be about 50, and increased registration fees are necessary to cover the costs of producing this quantity of preprints and handling other meeting costs. Consequently, the Executive Committee raised the *member* registration fee from $3.50 to $5.00 for the San Antonio Meeting. Students will be admitted free and allowed to purchase preprints at a discount.

Many members have felt that the differential between member and non-member registration fees during recent years has not been enough. This is particularly true with the non-member registration at the Dallas Meeting last year of 514, or 30 per cent. To correct this situation, the Executive Committee raised the *non-member* registration fee for the San Antonio Meeting to $10.00.

Along with this increase in non-member registration fees, a new plan will be started this year to permit $5.00 of the non-member fee to apply against the AIME initiation fee. The provision is that if the non-member's application is received within 30 days after the meeting, $5.00 will be forwarded from the Petroleum Branch Special Projects fund (in which all registration fees are deposited) to the Institute headquarters. In other words, the Institute will receive the applicant's full initiation fee, but he will get credit for $5.00 of his meeting registration fee. We believe this should be a very good incentive for non-members to join the Institute.

Attendance at Technical Sessions: Considerable discussion also developed after the Dallas meeting last year on the question of whether or not the social functions should be restricted to members, and a related question has been whether or not to restrict the technical sessions to those registered at the meeting. The Executive Committee considered both questions at the February meeting, at which a wide range of opinion was presented. The consensus was that we should maintain an open forum type meeting if at all possible, and the decision was to place a conspicuous sign in front of the entrance doors of each technical session saying that the session is open only to those persons registered at the meeting.

Pre-registration for Fall Meeting: An advance registration that was conducted for the 1953 Fall Meeting in Dallas was considered very successful. Although only 365 members took advantage of this method of registering, we believe it serves an important function. Firstly, it distributes some of the preprints before the meeting, which enhances discussion, and secondly, it permits members the first chance to buy tickets for the social functions. The advance registration will be used again this year, with the same fee to be charged for advance registration or for registration at the meeting.

Financing of Fall Meetings: In past years the local sections serving as "hosts" to the meetings have been financially responsible for the social functions. The total income and expense for social functions for the 1954 meeting in San Antonio is expected to be on the order of $30,000, and a number of us have felt that this is too great a financial burden to place on the local sections. Moreover, some have felt that the social functions are the responsibility of the Petroleum Branch in the final analysis, even though they may be conducted by the local sections. As a consequence, the Executive Committee made the decision to handle all income and expense for the San Antonio Meeting through the Branch Special Projects fund. The objective will be to break even on the meeting.

Petroleum Branch Membership Directory

The Executive Committee authorized the publication of a Branch membership directory if reasonably paid for by advertising, and this was carried out in the June issue of PETROLEUM TECHNOLOGY. The New York office of the Institute maintains a "directory address" on all members, which was placed on a set of 3 x 5 cards for the Petroleum Branch members. These cards were then sent to our printer in Dallas, the alphabetical listings were set from them, they were then placed in alphabetical order by cities. The directory was printed and bound into the June issue of PETROLEUM TECHNOLOGY in such a way that it can be easily removed for permanent reference. Advertising income just about paid for the cost of the directory, and we believe it will be an excellent service for the membership.

Assistance to Local Sections on Program Material

The Petroleum Section Conference, meeting in Dallas in October, 1953, recommended to the Executive Committee that a study be made of the possibility of providing the local sections with a "speaker panel" on the order of a distinguished lecture series. Burton Atkinson, accompanied by Roland Gouldy and William D. Owsley, studied the problem as a special committee and recommended that such a panel not be developed, because the committee believed that the effort entailed in local sections developing their own programs would engender more interest on the part of members and make the sections stronger than if the programs were arranged for them. However, this special committee recommended that all petroleum sections be informed by the Branch Office on a monthly basis of the papers presented before other sections. The Executive Committee adopted these recommendations, and the reporting of all papers to all other local sections has been carried out in recent months. The results seem to be very helpful. ★★★

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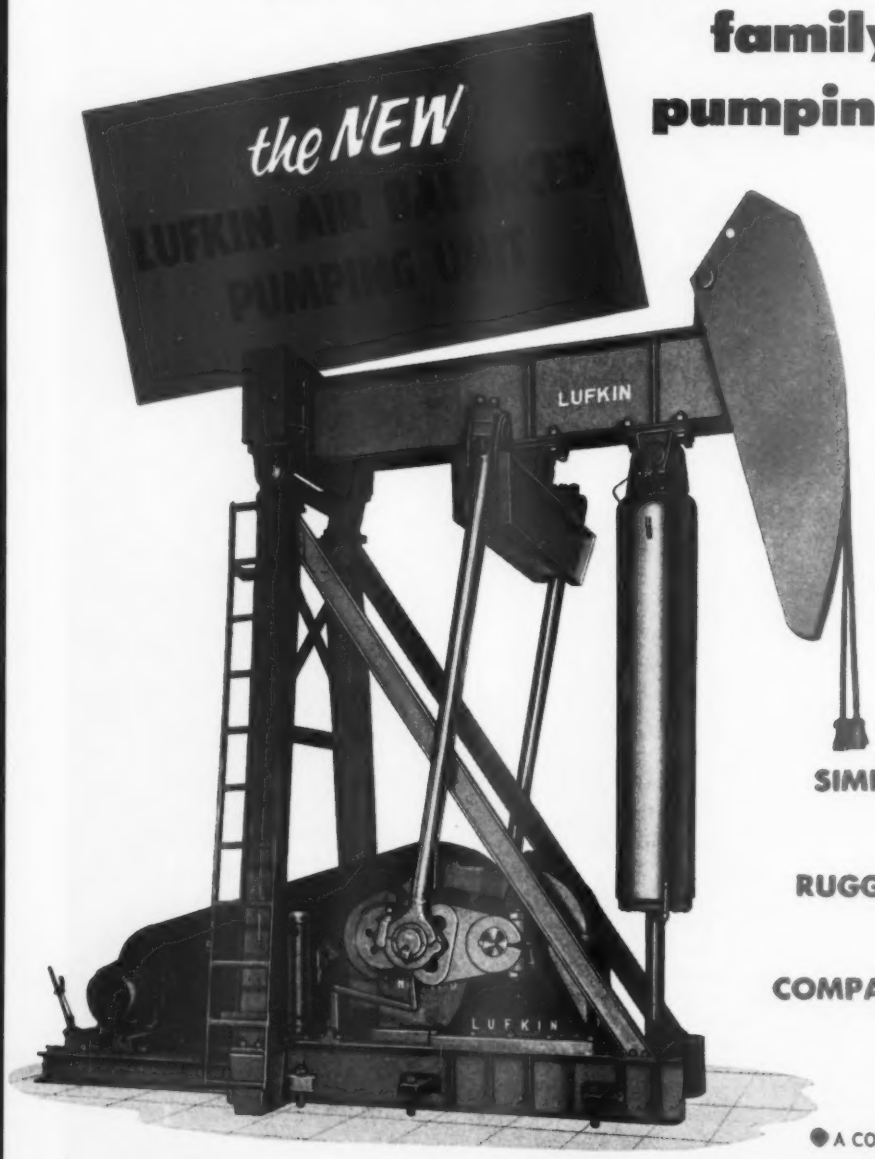

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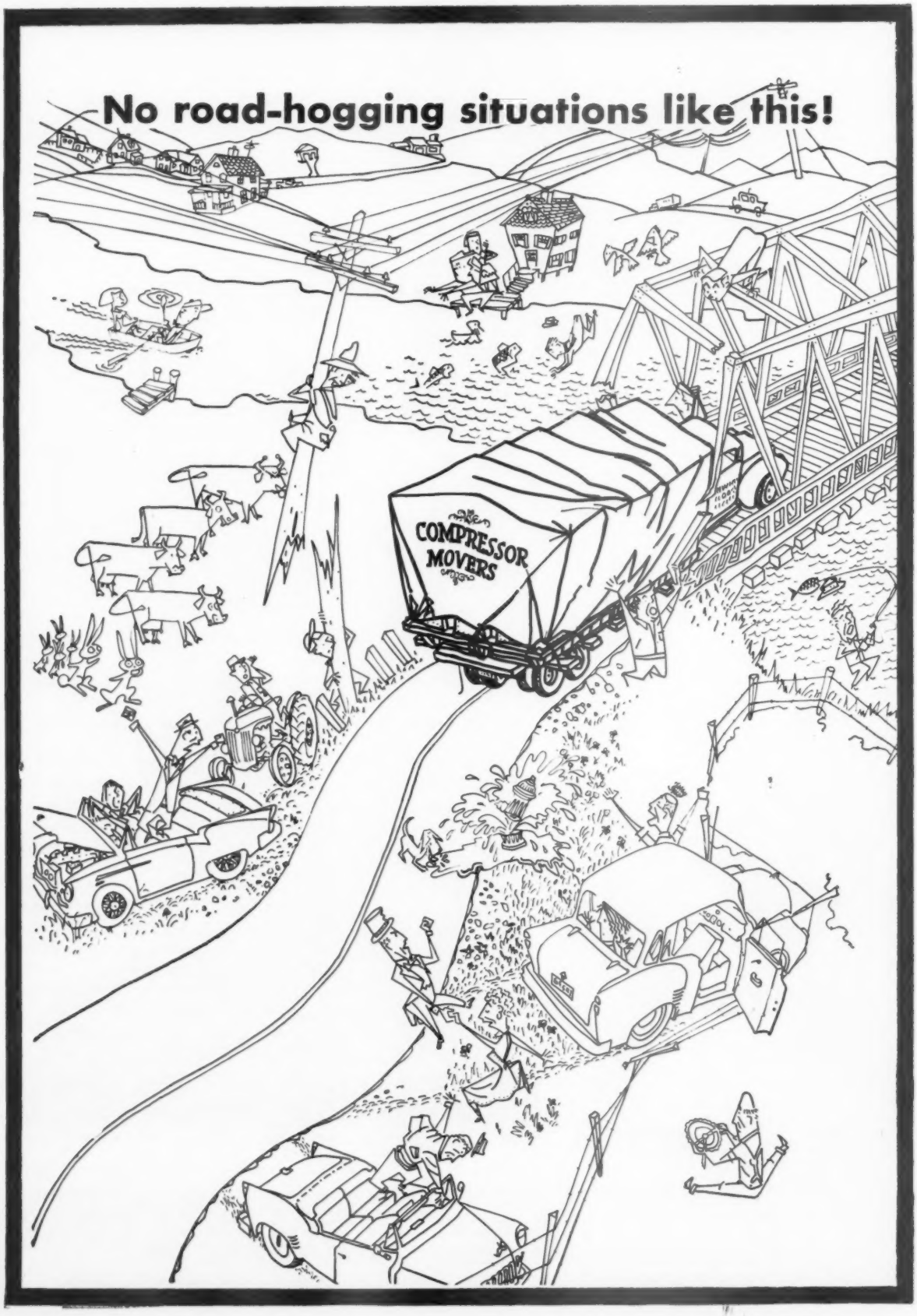
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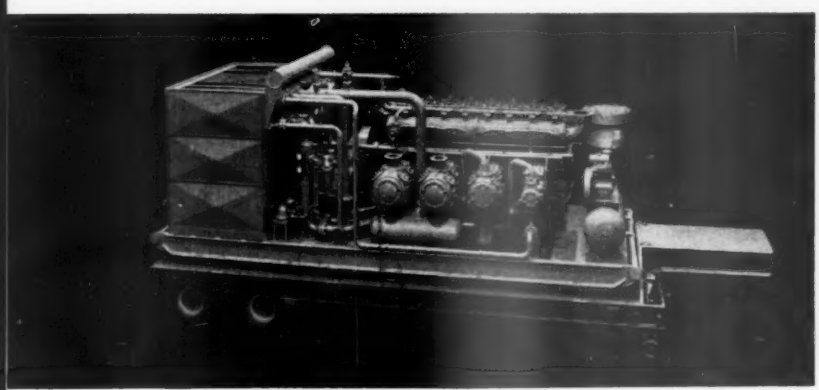

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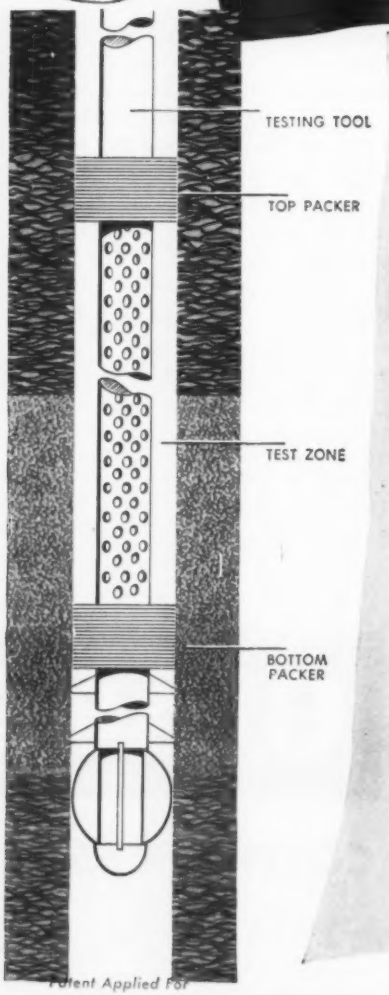

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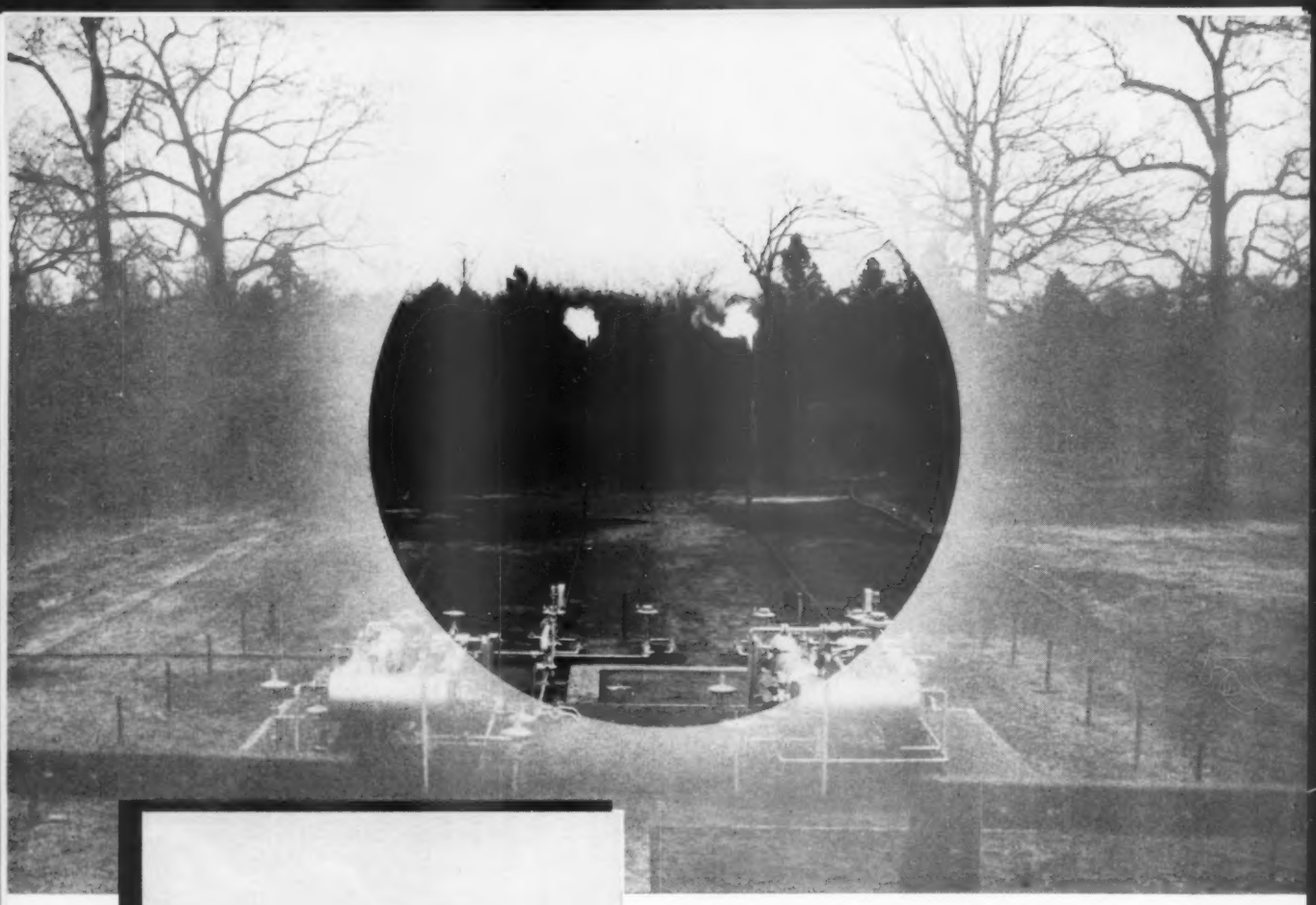

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A SIMPLIFIED ANALYSIS of UNSTEADY RADIAL GAS FLOW

J. S. ARONOFSKY
R. JENKINS
MEMBERS AIME

MAGNOLIA PETROLEUM CO.
DALLAS, TEX.

T. P. 3802

ABSTRACT

A simple means of predicting the flowing well pressure history in a natural gas reservoir has been developed. The differential equation for unsteady radial flow of gases through porous media was solved by numerical methods using electronic punch card machines. The results obtained from these calculations are presented in a generalized form which is believed to be most convenient for engineering use. These results are compared with those presented in a paper by Bruce, et al[1].

An effective radius of drainage has been defined which permits the equation of steady state gas flow to be used easily to predict well pressures in gas reservoir depletion. An equivalent effective radius of drainage is defined for liquid flow systems and a comparison is made of the gas solution to the liquid solutions.

INTRODUCTION

This paper presents a numerical method for describing the transient flow of gases radially through a porous medium from which the production rate is specified. The results obtained from these calculations are presented in a generalized form which is believed to be the most convenient for engineering use.

The principal application of these calculations should be to flow in natural gas reservoirs, in the interpretation of pressure drawdown tests, in the estimation of reserves, and in calculation of injection pressures required in gas injection and cycling operations. The evaluation of natural gas wells is based upon back-pressure tests in which measurements of production rate and flowing well pressure are made for periods of one, two, or more days. The flow is assumed to have stabilized at this time, and the observed values of pressure and production rate are used with standardized formulae to determine the well's allowable production rate. Furthermore, the results obtained from such a test of short time duration are extrapolated in such a manner to allow a prediction of what the well pressure will be at some future time for a specified (but possibly untested) flow rate.

The manner of conducting such back-pressure tests suggests several questions as follows:

1. What is the definition of stabilized flow and what factors determine the length of time required for the flow to become stabilized?

2. How may the recorded values of pressure and rate be utilized?

3. As the well is produced and the reservoir pressure falls, how will the flowing well pressure change? Can this flowing well pressure be predicted from the back-pressure test?

4. Are the results obtainable from the test influenced by a particular procedure used in obtaining the results?

5. Is it possible to estimate the gross reservoir permeability from back-pressure data?

It is not within the scope of this paper to provide solutions or even to discuss adequately all the above questions. However, in considering such matters, the

[1]References given at end of paper.

Manuscript received in the Petroleum Branch Office Feb. 17, 1953.

Discussion of this and all following technical papers is invited. Discussion in writing (3 copies) may be sent to the offices of the Journal of Petroleum Technology. Any discussion offered after Dec. 31, 1954, should be in the form of a new paper.

r_w – WELL RADIUS
r_d – EFFECTIVE DRAINAGE RADIUS
r_r – RESERVOIR RADIUS

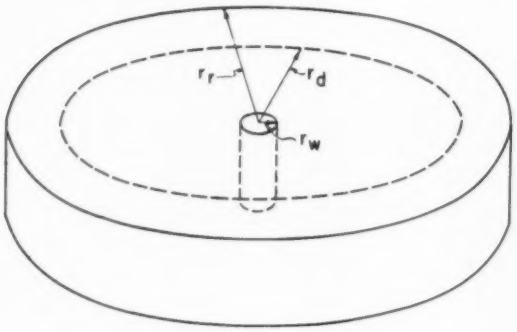

FIG. 1 — RADIAL RESERVOIR.

writers were stimulated to investigate transient gas flow, and have presented two scientific papers[1,2] on this subject. The purpose of the present paper is to present in reservoir engineering terms the results of this previous computational work, emphasizing the new concepts which were found. All of the results were obtained by means of calculations on high-speed electronic digital computing machines.

The results should be used with caution, taking into consideration the idealized assumptions that were made concerning the initial and boundary conditions, the rock properties, and the assumed properties of the gas itself.

BASIC ASSUMPTIONS

The differential equation which describes the flow of a gas through a porous medium has been described in the literature,[3] and its derivation is omitted here. For radial flow, this equation is

$$\frac{\partial^2(P/P_a)^2}{\partial r^2} + \frac{1}{r}\frac{\partial(P/P_a)^2}{\partial r} = \frac{2\phi\mu}{P_a K}\frac{\partial(P/P_a)}{\partial t} \quad . \quad (1)$$

(The symbols are listed at the end of the paper).

It is worthwhile to examine in detail the assumptions involved in deriving Equation (1):

1. The reservoir is disk shaped, with its center at the well bore; its top, bottom, and outer radius are impermeable.

2. The permeability to gas throughout the reservoir is constant and independent of pressure.

3. The only flowing phase is a gas of constant composition.

4. The density of this gas is directly proportional to the pressure (Boyle's Law).

5. The flow obeys Darcy's Law, i.e., is in the viscous range.

6. The viscosity of the gas is constant.

7. Gravitational forces are negligible.

It is necessary to examine these assumptions in greater detail to evaluate their influence on the subsequent solutions to the equation. First, it is apparent that no reservoir will have the exact geometric shape of a disk with a well at its center, as required by the first assumption. However, it is customary to assume that the performance of a single well in a field developed in a square or staggered pattern will satisfy this condition approximately. This assumption is considered reasonable, since Muskat* has demonstrated for the liquid case that the radial-flow type formula will give the flow capacity of a well even if the external boundary is no longer circular but has a radically different geometry.

The second assumption, which deals with gas permeability, is again an idealization. It is known that core samples show a variation in permeability to gas with pressure (particularly at low pressures) which is usually described as "gas slip." This effect is probably negligible because of the high pressures which are generally associated with gas reservoirs.

A free gas field, or a "condensate" field producing at a very high gas-oil ratio should satisfy the third requirement.

In the fourth assumption, many important cases exist where deviations from Boyle's Law are not large. When these deviations are severe, the entire problem must be re-examined in order to make appropriate corrections to the calculations based on PVT measurements. Discussion of the methods for considering such corrections is beyond the scope of this paper.

Assumptions 5, 6, and 7 may be relaxed sufficiently to handle many cases which would be encountered in the field. However, there are some cases where variations in gas viscosity are of sufficient magnitude that they require independent consideration.

METHODS OF CALCULATION

All the calculations of pressures and rates shown in this paper are the results of solving the differential Equation (1) for radial gas flow. These calculations were made using numerical solutions available from two different sources in the literature.[3,4] In both cases, these solutions were found by calculating the changes in pressure at a series of radially spaced points in the reservoir after some interval of time, and repeating this process by means of IBM electronic punch card calculating machines to obtain the complete curves.

Prior to making the actual step-by-step calculations of the pressure change it is necessary to reduce the differential equation to an appropriate difference equation and this difference equation in turn is solved by the numerical method. It is not within the scope of this paper to discuss the various difference equations that may be used to represent Equation (1) since at least two such

*See page 200 of Ref. 5.

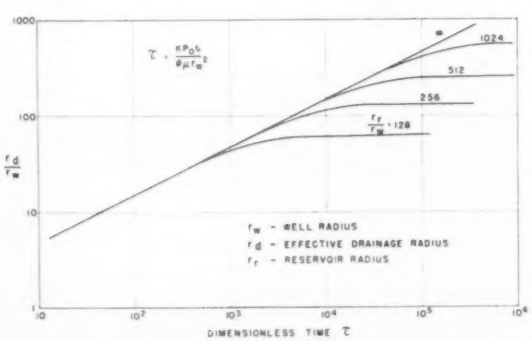

FIG. 2 — DRAINAGE RADIUS AS A FUNCTION OF TIME.

techniques are described elsewhere.[2-4] The present writers made use of a simple device, called the "steady-state core," which reduces the amount of machine time required to obtain numerical solutions by means of the punch card equipment.

THE STEADY-STATE CORE*

The first gas withdrawn from a well originates very close to the well. As the reservoir is further depleted, the area from which the gas is being removed has an increasingly larger outer radius. A short time after production of the well begins, the area of the reservoir close to the well is essentially under steady-state conditions. Therefore, the steady-state radial flow formula can be used to relate the pressure drop in this region to the production rate, and the difference equation need not be applied here. This gives a new and larger, "ficticious," well radius to use in the difference equation to determine the size of the time steps.

The writers used this concept of steady-state cores in performing the calculations described in Ref. 2. Calculations using the actual well radius were made to overlap those using the steady-state cores, and the differences were found to be negligible.

The writers believe that this steady-state core principle can be applied to many other physical problems involving transient flow to or from a well. It is not yet known what factors may limit the application of this method.

THE CONSTANT-RATE PROBLEM

A problem of practical importance to the reservoir engineer is illustrated in Fig. 1 which shows a well passing through the center of a sand body of uniform thickness and circular cross section containing gas at a uniform pressure P_o. The top, bottom, and outer boundary of this sand are impervious to the gas, which can escape only through the well. At time, $t = O$, withdrawal of gas through this well is begun and maintained thereafter at a constant rate, Q, as measured at standard conditions.

The problem then is to determine the pressure distributions in the reservoir at some later time, $t > O$, with particular emphasis placed on determining the pressure at the well bore at any time. This type problem has been solved for various dimensionless flow rates and for various ratios of reservoir radius to well radius, $\frac{r_r}{r_w}$, by means of the punch card machines with the use of the steady-state core.[2] This is, of course, a transient phenomenon, and the proper equation for expressing the pressure distribution at any time is the original differential equation, (1). However, it is possible to express a relationship between the flow rate, Q, and the well pressure, P_w, by the use of a very simple concept called the effective drainage radius.

EFFECTIVE DRAINAGE RADIUS

The well known steady-state formula for radial gas flow may be written as

$$ln\left(\frac{r_d}{r_w}\right) = \frac{\pi K h P_o}{Q P_{sc} \mu}\left[\left(\frac{P_o}{P_{sc}}\right) - \left(\frac{P_w}{P_{sc}}\right)^2\right]. \quad (2)$$

*This idea was first brought to the writers' attention by Prof. S. P. Frankel of the California Institute of Technology.

It is desired to interpret the above Equation (2) so that it will always represent properly the flowing well pressure, P_w, and the production rate, Q, for the entire time history of the depletion problem. In other words, the steady-state Equation (2) is forced to represent the transient relationship between P_w and Q by proper definition of the remaining terms P_s and r_d in Equation (2).

Let P_s represent the bulk average pressure in the reservoir at any instant of time. The average pressure, P_s, is defined to be the pressure which would be found if flow at the well were stopped and the pressure in the reservoir allowed to equalize. This definition is particularly useful because this pressure value can be evaluated by at least three different methods as listed below:

1. By taking a weighted average of the pressure distribution at any instant of time. These pressures are available from the IBM results.
2. By shutting in the well and allowing the well pressure to build up to its stabilized value.
3. By solving the material balance equation for the total reservoir fluid to determine P_s. In this case $P_s = P_o\ (1 - \overline{Q}\Theta)$, where $\overline{Q}$ and Θ are dimensionless quantities defined in the symbols list.

The advantage of such a definition of P_s is the possibility of using method 2 or 3 under actual field conditions, or employing the customary field data.

The remaining term that has not yet been defined is the *effective drainage radius*, r_d, which must be allowed to take on any value required to force the steady-state Equation (2) to represent the transient solution.

It is instructive to make some plots to determine how the effective drainage radius, r_d, will vary with time. Such plots are shown in Figs. 2, and 3. Fig. 2 is a plot of the drainage ratio, r_d/r_w, versus dimensionless time, τ^*. This plot emphasizes the condition that, initially, the effective drainage radius, r_d, starts out near the well bore and advances radially outward as the flow continues. Furthermore, the effective drainage radius is independent of the outer boundary (or reservoir radius, r_r during the initial transients.

During the later life of the reservoir, the situation is reversed and the drainage radius is independent of the well radius, but depends entirely on the outer reservoir radius, r_r, as is shown clearly in Fig. 3, which is a

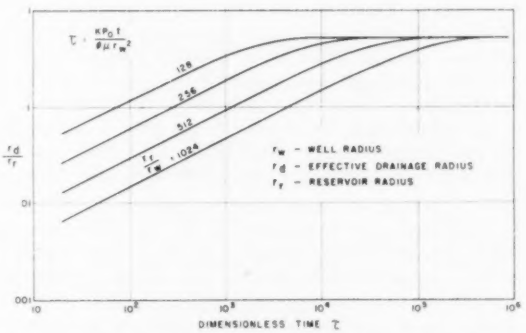

FIG. 3 — DRAINAGE RADIUS AS A FUNCTION OF TIME.

*The symbol τ is a dimensionless time defined in terms of the well radius, whereas Θ is another dimensionless time defined in terms of the outer radius, r_r. Both symbols are used depending upon whether it is desirable to describe the time parameter in terms of the inner or outer radius.

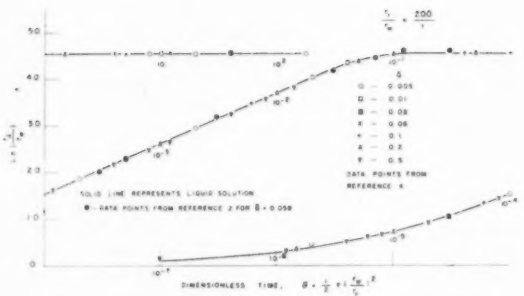

FIG. 4 — DRAINAGE RADIUS VERSUS TIME FOR VARIOUS RATES.

plot of the ratio, r_d/r_e, versus dimensionless time, τ. Plots are given for different ratios of outer to inner boundaries, r_e/r_w, of 128, 256, 512, and 1,024, and it is seen that in all cases the effective drainage radius builds up to a value of approximately *one-half the reservoir radius, r_e*. Thus, we see different curves at the early time period which all build up to the *same stabilized value* of r_d/r_e.

The curves of Figs. 2 and 3 were determined originally from the computational results of Ref. 2 for two different production rates. Actually, the original results were determined for a ratio of outer to inner boundary, r_e/r_w, of 1,024 and the other curves of Fig. 2 or 3 were then calculated by proper relocation of the steady-state core.

The paper by Bruce, Peaceman, Rachford, and Rice[4] contains extensive data that applies to the same problem reported in this paper so it is possible to correlate their results in terms of the effective-drainage-radius concept defined in Equation (2).

The results from Ref. 4 and Ref. 2 are plotted in terms of the drainage radius ratio, $ln\ r_d/r_w$, versus the dimensionless time, $\frac{1}{2}\tau \left(\frac{r_w}{r_e}\right)^2$, or, Θ, as indicated in Fig. 4. The plotted points represent numerical solutions of Equation (1) for a reservoir radius ratio $r_e/r_w = 200$. The legend of Fig. 4 shows that data from Ref. 4 are plotted for seven different dimensionless rates, $\overline{Q}$, covering the range from the minimum of 0.005 to the maximum value of 0.5. The striking feature of this comparison is that all the points approximately fall on a smooth curve for a 100-fold change in rates over the enormous time range of Θ from 10^{-7} to 10^{-2}. Furthermore, this takes on even more significance when it is realized that the solid line in Fig. 4 represents the solution for *transient liquid flow*. This can be determined directly from the $P_{(\tau)}$ functions tabulated in Ref. 7 or from the basic solution described in Ref. 3. The mathematical formulation of the effective drainage radius for the liquid system is given in the appendix of this paper. Examination of Fig. 4 shows that the comparison between the results of two separate research groups using completely different computing methods is quite good. Significant factors necessary to a proper understanding of Fig 4 are summarized below:

1. The plotted points of Fig. 4 (which are obtained from numerical solutions of gas flow for various rates) almost coincide with the solid line which in turn represents the solution for transient liquid flow in a radial system.

2. The quantity, $ln\left(\frac{r_d}{r_w}\right)$, represents a type of correlation function that correlates well pressure, P_w, and time, Θ, for both transient gas flow and transient liquid flow for all constant rate cases studied up to a maximum gas rate, $\overline{Q}$, of at least 0.5. It appears that this correlation is reasonably good over the entire time range for $\frac{r_e}{r_w} = 200$, and that a similar correlation can be made for any other reservoir radii where r_e is much larger than r_w.

3. The effective drainage radius stabilizes at approximately one-half the outer radius after only a small percentage of fluid in place has been removed. As shown in the appendix a more accurate stabilized value for the liquid case is $0.472r_e$ and it is, therefore, suggested that this value be used in numerical calculations for gas flow as well as liquid flow. It should be observed that for very high production rates the well pressure will decline to zero prior to stabilization of the effective drainage radius.

4. Equation (2) can be used to make a good prediction of the well pressure in gas systems for any specified production rate, $\overline{Q}$, less than 0.5 and for any value of outer radius of the reservoir large compared with the well radius and for any time, Θ.

5. The correlation function of Fig. 4 offers a means for estimating the gross permeability-to-porosity ratio of a gas reservoir in a manner similar to that used for liquid systems.

6. Equation (2) does *not* represent a unique solution to the differential Equation (1). It is merely a correlation function that is useful only for a limited range of production rates, $\overline{Q}$. A careful examination of the data reveals that there is a systematic deviation in this correlation function for increasing values of $\overline{Q}$. For instance, the quantity, $ln\left(\frac{r_d}{r_w}\right)$, for $\overline{Q} = 0.5$ differs from the quantity for $\overline{Q} = 0.005$ by 1.8 per cent where $\Theta = 0.008$. Similar deviations occur at other values of Θ. These deviations, although present in the data plotted in Fig. 4, are so small as to be generally unobservable because of the chosen method of plotting. It is anticipated that increasingly larger deviations would occur for larger values of $\overline{Q}$. Conversely, the correlation function approaches the liquid curve in the limit as the gas rate approaches zero.

7. The dimensionless rate, $\overline{Q} = 0.5$, which is the largest gas rate shown in Fig. 4, represents an actual production rate of almost 1 million standard cu ft/day/ft of sand using the reasonable values for initial pressure, permeability, and gas viscosity of 1,000 psi, 100 md, and 0.017 cp, respectively. Also, this rate is so large that only about 1 per cent of the fluid in place can be recovered before the well pressure becomes zero.

WELL PRESSURE CALCULATIONS FOR STABILIZED FLOW

The use of Equation (2) for calculating the well pressure becomes very simple for values of Θ larger than approximately 0.3, since the effective drainage radius becomes stabilized at approximately $0.472r_e$. Then, Equation (2) reduces to

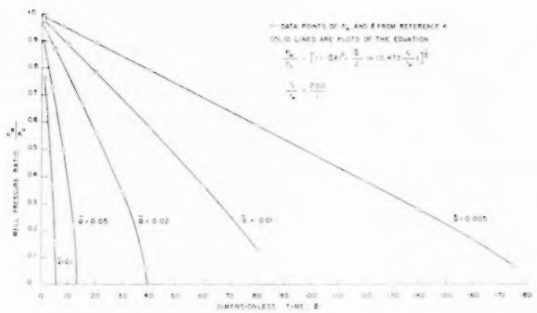

FIG. 5 — WELL PRESSURE VERSUS TIME FOR VARIOUS RATES.

$$P_w/P_o = \left[(1-\bar{Q}\Theta)^2 - \frac{\bar{Q}}{2} ln\left(0.472\frac{r_r}{r_w}\right)\right]^{1/2} \quad . \quad (3)$$

where the (P_a/P_o) term in Equation (2) is replaced by $(1-\bar{Q}\Theta)$ from material balance considerations. Solutions of Equation (3) are illustrated as solid lines in Fig. 5 for dimensionless rates, $\bar{Q}$, of 0.005, 0.01, 0.05, and 0.1 where the outer boundary is $200r_w$. The plotted points in Fig. 5 are taken from the results of Ref. 4, and it is demonstrated that solid line solutions of Equation (3) agree very well with the calculated data points.

It is worthwhile to mention that similar sets of curves can be prepared for the constant-pressure case but such data are not presented in this paper. However, it was found that the effective drainage radius builds up to a stabilized value for the constant-pressure cases as well as for the constant-rate cases.

APPENDIX

EFFECTIVE DRAINAGE RADIUS FOR LIQUID SYSTEMS

The definition of effective drainage radius for a liquid system is

$$ln\left(\frac{r_d}{r_w}\right) = \frac{2\pi Kh}{Q\mu}\left[P_a - P_w\right] \quad . \quad . \quad . \quad (4)$$

and the average pressure, P_a, is defined in terms of the material balance condition and reduces to a very simple form for constant production rate.

$$P_a = P_o - \frac{Q\mu r_w^2\tau}{\pi r_r^2 hK} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where the dimensionless time τ, is analogous to the τ for gas flow. However, the τ for liquid flow is usually expressed in the following form.[5,6,7]

$$\tau = \frac{Kt}{\phi\mu r_w^2\beta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Using the definition of Equation (6), Equation (5) is valid only if r_r is much larger than r_w. Eliminating P_a between Equations (4) and (5) leads to

$$ln\left(\frac{r_d}{r_w}\right) = \frac{2\pi Kh}{Q\mu}(P_o - P_w) - 2\tau\left(\frac{r_w}{r_r}\right)^2 \quad . \quad (7)$$

Analytical solutions for such liquid systems are available in the literature[5,6,7] in terms of the quantity, $\frac{2\pi Kh(P_o - P_w)}{Q\mu}$, which Hurst and Van Everdigen[7] call the "cumulative pressure drop for a unit rate of production at the well." The symbol $P_{(\tau)}$ is used to represent this quantity. Equation (7) may now be written in terms of this $P_{(\tau)}$ function

$$ln\left(\frac{r_d}{r_w}\right) = P_{(\tau)} - 2\tau\left(\frac{r_w}{r_r}\right)^2 \quad . \quad . \quad . \quad . \quad . \quad (8)$$

The function, $ln\left(\frac{r_d}{r_w}\right)$, is now completely defined in terms of the known $P_{(\tau)}$ function so $ln\left(\frac{r_d}{r_w}\right)$ can be evaluated for any value of τ for a specified outer boundary simply by first evaluating $P_{(\tau)}$ according to the details given in Ref. 7. Such a plot is shown as the solid line in Fig. 4 where $\Theta = \frac{1}{2}\tau\left(\frac{r_w}{r_r}\right)^2$.

It is instructive to determine the stabilized value of $ln\left(\frac{r_d}{r_w}\right)$ for large values of τ for a case where $(r_r/r_w)^2$ is much larger than unity. The $P_{(\tau)}$ function becomes

$$P_{(\tau)} = \left(\frac{r_w}{r_r}\right)^2 + 2\tau\left(\frac{r_w}{r_r}\right)^2 - \frac{3}{4} + ln\left(\frac{r_r}{r_w}\right) \quad . \quad . \quad (9)$$

and $ln\left(\frac{r_d}{r_w}\right)$ becomes

$$ln\left(\frac{r_d}{r_w}\right) = ln\left(\frac{r_r}{r_w}\right) - \frac{3}{4} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where the $(r_w/r_r)^2$ term is considered to be negligible. The ratio r_d/r_r can be evaluated because

$$ln\left(\frac{r_d}{r_r}\right) = -\frac{3}{4} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

and

$$\left(\frac{r_d}{r_r}\right) = e^{-3/4} = 0.472 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

Another interesting condition is that the function, $ln\left(\frac{r_d}{r_w}\right)$, is almost equal to the $P_{(\tau)}$ function for the initial transient where Θ is extremely small and P_a is almost equal to P_o.

ACKNOWLEDGMENT

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SYMBOLS LIST

h = formation thickness, cm

K = permeability, darcys

P = pressure within reservoir, atm

P_a = bulk average pressure in reservoir, atm

P_o = initial pressure in reservoir, atm

P_s = pressure at standard conditions, atm

$P_{(\tau)}$ = function defined in Ref. 7

P_w = well pressure, atm

Q = production rate into well, standard cc per sec

$\bar{Q} = \dfrac{2QP_o\mu}{\pi P_o^2 Kh}$ or dimensionless flow rate

r = radial distance from center of well, cm

r_d = effective drainage radius, cm

r_e = reservoir radius (outer boundary), cm

r_w = well radius, cm

t = time, sec

β = liquid compressibility, atm^{-1}

μ = viscosity, cp

ϕ = porosity, fraction

$\tau = \dfrac{KP_o t}{\phi\mu r_w^2}$ or dimensionless time parameter for gas

$\tau = \dfrac{Kt}{\phi\mu r_w^2\beta}$ or dimensionless time parameter for liquid

$\Theta = \frac{1}{2}\,\tau\left(\dfrac{r_w}{r_e}\right)^2$

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RESISTIVITY LOGGING in THIN BEDS

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ABSTRACT

Conventional resistivity logs consisting of a short normal, a long normal, and one or more long lateral curves do not give data that allow a complete quantitative interpretation in beds thinner than 20 ft. Reservoir rocks usually exhibit zones of continuous homogeneity of quite limited thickness where the long lateral curves become useless because of adjacent bed effects and boundary phenomena. If the beds are 12 ft or thicker, the short and long normals may be used for qualitative interpretation, which can be streamlined by the application of simplified departure curves. For beds of a thickness less than twice the long normal spacing, this procedure breaks down.

The combination of the limestone curve, the laterolog or guard electrode log, and the microlaterolog permit quantitative interpretation for beds that are at least 10 ft thick, provided the mud resistivity and the hole diameter are known with sufficient accuracy.

For beds thinner than 10 ft, combinations of the microlaterolog with short spaced laterologs and pseudo laterologs appear to be promising. Interpretation of these curves again requires the application of simplified departure curves. Resolution of various possible combinations was analyzed using departure curve data calculated on the Whirlwind I computer at the Massachusetts Institute of Technology.

A field example is shown using the microlaterolog-microlog combination, and the combination of a 6-in. modified laterolog plus a 6-in. pseudo laterolog.

INTRODUCTION

For the purpose of quantitative interpretation of resistivity logs in porous formations, we want to obtain two essential quantities from the logs, namely, the true resistivity of the undisturbed formation, R_t, and the resistivity of the part of the formation invaded by mud filtrate, R_i. The apparent resistivities of all conventional logging devices are functions of these two parameters and are also influenced by a third unknown parameter, the diameter of the invaded zone, d_i.

It has been shown[1] that from the normal curves alone it is impossible to arrive at a unique solution for the three unknowns, R_i, R_t, and d_i. In very thick homogeneous beds, if invasion is not too deep, we can obtain a fair approximation to R_t from the long lateral curves and then use the two normal curves to find R_i and d_i. Even under the most favorable conditions, the resolution of this system is not very good. The short normal does not give a reasonable approximation to R_i unless invasion is very deep ($d_i > 16$ hole diameters). For very deep invasion, however, the long laterals no longer approximate R_t.

For bed thickness between 20 and 40 ft, the long laterals are affected appreciably by the adjacent beds; and the curves are distorted by boundary anomalies to the extent that they lose their quantitative usefulness in most cases. For the same bed thicknesses, the normal curves still function reasonably well.

Although it is impossible to find unique solutions for R_i and R_t using the normal curves alone, we can obtain a reasonable approximation for the ratio R_i/R_t through the use of simplified departure curves. This fact was brought to our attention by A. J. de Witte, geologist with Continental Oil Co. As the magnitude of R_i/R_t is a major clue to the presence of oil in formations, this method can be used to good advantage for qualitative analysis and will be discussed in somewhat greater detail.

With the aid of suitable bed thickness corrections, the analysis of the normal curves may be used for bed thicknesses larger than 12 ft. For thinner beds, the method rapidly loses its resolution; and we have to resort to different types of resistivity logs if we want to attempt to analyze the curves quantitatively.

The inadequacy of conventional resistivity curves in thin beds is far more serious than generally realized. Fig. 1 shows a conventional E. S. with a 16-in. and 64-in. normal and a 16-ft lateral through a section of Lansing-Kansas City lime, in comparison to a guard electrode survey through the same section in a neighboring well. The porous zones, which show up as low resistivity breaks on the guard electrode log, are completely masked by adjacent bed effects and boundary anomalies on the conventional curves. Even the short normal shows most of the porous zones only as vague deflections and in many cases fails to register their

[1]References given at end of paper.

Manuscript received in the Petroleum Branch office Sept. 14, 1953. Paper presented at the Petroleum Branch Fall Meeting in Dallas Oct. 19-21, 1953.

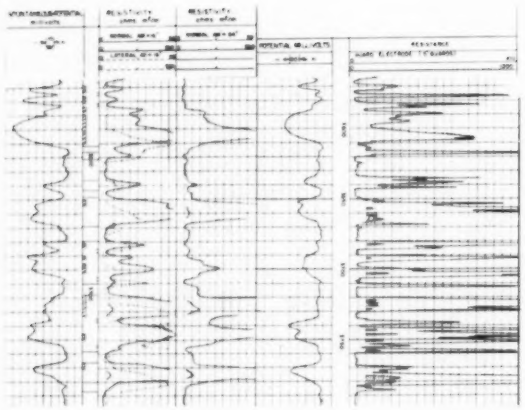

FIG. 1 — A CONVENTIONAL ELECTRIC LOG SURVEY THROUGH A SECTION OF LANSING-KANSAS CITY LIME. AND A GUARD ELECTRODE LOG THROUGH THE SAME SECTION.

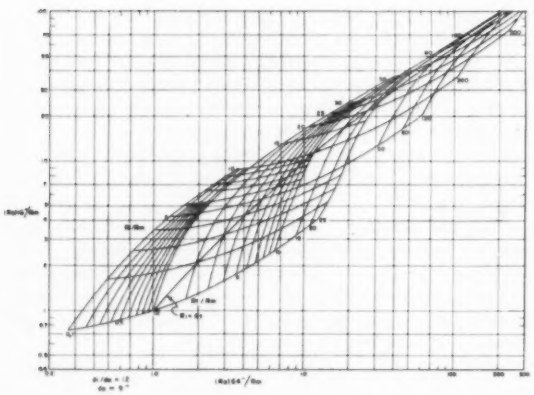

FIG. 2 — SIMPLIFIED DEPARTURE CURVES — 16-IN. AND 64-IN. NORMAL DEVICES.

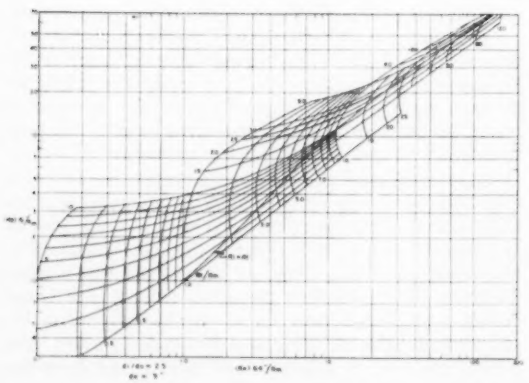

FIG. 3 — SIMPLIFIED DEPARTURE CURVES — 16-IN. AND 64-IN. NORMAL DEVICES.

presence completely. It is obviously out of the question to make a quantitative analysis for the porous producing horizons from the conventional curves in cases like this.

SIMPLIFIED DEPARTURE CURVES FOR THE NORMAL DEVICES

As stated before, the normal curves cannot give unique solutions for R_i, R_t, and d_i. If, however, we assume a certain value of d_i, then two normal apparent resistivities suffice to determine R_i and R_t. These determinations are most easily carried out with the help of simplified departure curves of the type shown in Figs. 2 and 3. Each graph is made up for a certain hole diameter and a given value of d_i/d_h. After measuring the apparent resistivities for the 16-in. normal and 64-in. normal from the logs, we find a value for R_i/R_m and R_t/R_m from each chart corresponding to each assumed value of d_i/d_h (where d_h is the hole diameter).

Fig. 4 shows a conventional E. S. through the Sussex sand in a well in the Meadow Creek field, Wyo. We notice that the long lateral curve is distorted while the normals appear to give reliable deflections, especially in the center portion of the bed (3,550-67).

The mud resistivity, R_m, at formation temperature is 2.0 ohmmeters. The hole diameter is 9 in. The apparent resistivities of the 16-in. normal and the 64-in. normal are respectively: $(R_a)16 = 28\Omega m$; $(R_a)64 = 18.5\Omega m$. This gives $(R_a)16/R_m = 14$ and $(R_a)64/R_m = 9.25$.

For simplified departure curves as shown in Figs. 2 and 3, we obtain the following possible answers:

d_i/d_h	R_i/R_m	R_t/R_m	R_i/R_t
12	15.5	3.7	4.19
5	18.0	6.0	3.00
2.5	26.0	6.2	4.2

The ratio of R_i/R_t is indicative of the fluid content of the formation. Various methods have been described to calculate the water saturation from this ratio.[2,3]

Continental Oil Co. at present uses a set of nomographs based on analysis of the SP curve and on the equations 20 and 22 given in Ref. 3. The value of the SP curve for the sand under analysis is 34 mv. The connate water resistivity for the Sussex sand is $0.3\Omega m$ at formation temperature. This gives a K factor of 41.3 in the equation $SP = K_t \log R_{mf}/R_w$.* Corrected to 77°F., the K factor becomes $K_{77} = 40.3$.

Using the nomograph for $K_{77} = 40$ shown in Fig. 5, we find the following values for the water saturation S_w:

R_i/R_t	S_w
4.19	100 per cent
3.0	70 per cent
4.2	100 per cent

The above S_w values, obtained for assumed d_i/d_h ratios ranging from 2.5 to 12, show that in all probability the sand contains only water. Although by this procedure, we do not arrive at a unique quantitative answer, the qualitative distinction between oil and water bearing formations can be made in most cases, where the beds are thick and homogeneous enough for the normal curves to give reliable deflections.

*The coefficient K_t used in this equation is equal to the product αK in the Schlumberger terminology where K is the SP coefficient for a clean sand and α is the ratio of pseudo static SP of a shaly sand to the static SP of a clean sand (for the same values of R_{mf} and R_w).

A similar procedure of interpretation using simplified departure curves could be worked out for other conventional curves, say a short normal and one long lateral. In most cases this would require correcting the long laterals for bed thickness effects as may be done by the use of the maximum-minimum formulae.[4] These corrections, however, all neglect the influence of the drill hole and of invasion; and they are, therefore, not very accurate. In view of the much larger number of lateral spacings in use than the number of standard normal spacings, it is far more practical to use a simplified departure curve system for the normals in areas where two normal curves are run.

DETERMINATION OF INVADED ZONE RESISTIVITY FROM THE MICROLATEROLOG

A more direct approach to the determination of R_i and R_t in thin sands can be made by measuring the invaded zone resistivity directly with a microlaterolog.[5]

To find R_i the reading of the microlaterolog has to be corrected somewhat to take the presence of mudcake into account. To do this, one or two microlog curves are used and mudcake corrections are made with the aid of suitable departure curves.[5]

The determination of R_i from the microlaterolog assumes that the invaded zone has a fairly constant resistivity from the boreface out to its diffuse contact with the undisturbed formation. Evidence in support of this assumption has been given by experimental work on resistivity distributions in invaded zones of porous formations.[6]

Fig. 6 shows a microlaterolog and conventional microlog through the Shannon sand in the West Sussex field, Johnson County, Wyo. In the section from 2,773-2,776, the microlaterolog apparent resistivity is approximately 15 ohmmeters. Both the microinverse and the micronormal curves read 9.2 ohmmeters. The values of R_m and R_{mc} were measured as 1.6 and 1.79 ohmmeters (corrected to formation temperature). This gives R_i ½-in./R_{mc} = 5.15; R_t-in./R_{mc} = 5.15; and $R_{mLL}/R_{mc} = 8.4$. This gives for the mudcake thickness (MCT) = .12 in. Using R_{mLL}/R_{mc} = 8.4 and MCT = .12 in., we find from the departure curves for the 9/16-9/16-9/16 microlaterolog, that $R_i/R_{mc} = 9.5$ or $R_i = 17\ \Omega_m$.

THE LATEROLOG-LIMESTONE CURVE COMBINATION

If R_i is determined from the microlaterolog, we have two remaining unknowns, namely, the extent of invasion (described by the invasion diameter d_i) and the true resistivity R_t. Theoretically any two additional apparent resistivity readings which are not influenced by adjacent bed effects or distorted by boundary phenomena, should give us sufficient information to solve for d_i and R_t. A further criterion is that the current patterns of the two devices are sufficiently different so that the registered apparent resistivities are related to the unknown quantities by dissimilar (and therefore independent) equations.

For beds thicker than 10 ft the combination of the laterolog[7] and the limestone device fulfills in most cases the above conditions.

The solution of the two simultaneous equations given by the relations between the laterolog and limestone curve apparent resistivities and d_i and R_t can be represented graphically by simplified departure curves. The departure curve charts can be made up for given values

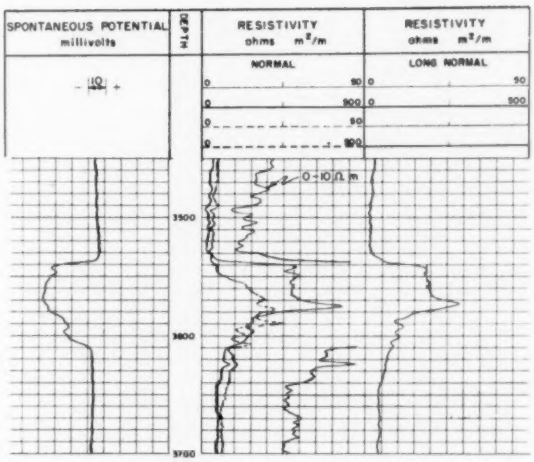

FIG. 4 — A CONVENTIONAL ELECTRIC SURVEY, SUSSEX SAND, MEADOW CREEK FIELD, WYO.

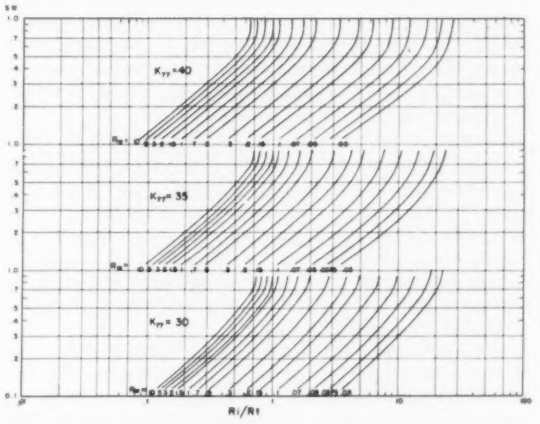

FIG. 5 — NOMOGRAPH FOR SATURATION CALCULATIONS.

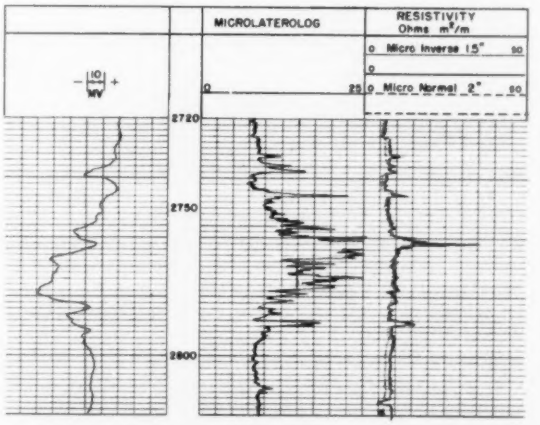

FIG. 6 — MICROLATEROLOG AND CONVENTIONAL MICROLOG, SHANNON SAND, WEST SUSSEX FIELD, WYO.

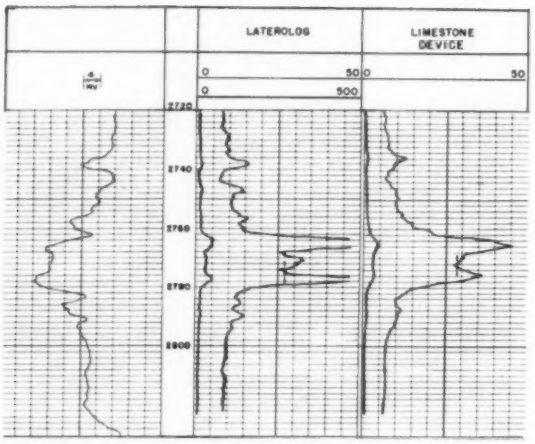

FIG. 7 — 16-IN. LATEROLOG — 7-IN. AND 37-IN. LIMESTONE CURVE, SHANNON SAND, WEST SUSSEX FIELD, WYO.

of R_t/R_m. The abscissa carries the ratio of the laterolog apparent resistivity to R_m (R_{LL}/R_m), while the ordinate carries the ratio of the limestone curve apparent resistivity to the mud resistivity (R_{Ls}/R_m). The departure curves are plotted as two families of curves: one set representing constant values of R_t/R_m, while the other set represents given values of d_t/d_m.

In this form the charts are completely direct reading: a set of values of R_{LL}/R_m and R_{Ls}/R_m obtained from the logs, determines the position of a point on the departure curve chart. By visual interpolation, we easily obtain the values of R_t/R_m and d_t/d_m corresponding to this point.

Fig. 7 is a copy of a 16-in. laterolog-7 and a 37-in. limestone curve through the same section of Shannon sand that was shown in Fig. 6.

We shall apply a simplified departure curve analysis to the same zone for which R_t was found from the microlaterolog (2,772-76). Although the readings are taken in this 3-ft zone, the immediately adjacent beds have resistivities that differ by a sufficiently small amount, so that for practical purposes adjacent bed effects can be neglected.

The laterolog apparent resistivity in this zone is

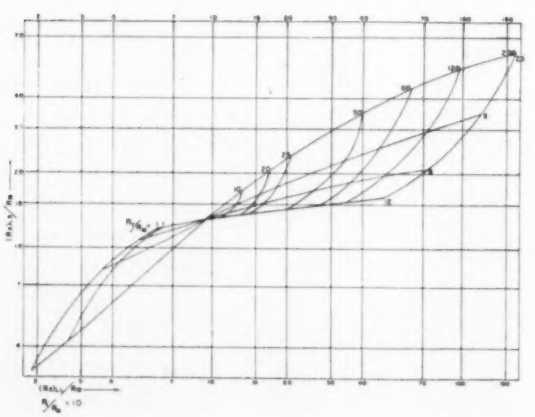

FIG. 8 — SIMPLIFIED DEPARTURE CURVE FOR LATEROLOG LIMESTONE CURVE COMBINATION.

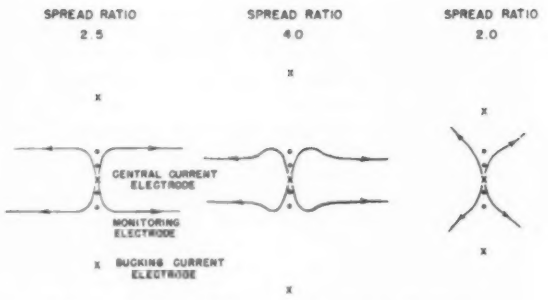

FIG. 9 — THE EFFECT OF SPREAD RATIOS.

approximately $27\Omega m$ while $R_{Ls} = 28.5\Omega m$. The mud resistivity at formation temperature is $1.6\Omega m$. This gives $R_{LL}/R_m = 16.9$ and $R_{Ls}/R_m = 17.8$. The foregoing microlaterolog and analysis gave $R_t = 17\Omega m$ or $R_t/R_m = 10.6$.

We select a departure curve chart for $R_t/R_m = 10$ for a close enough approximation. The chart is shown in Fig. 8. Using the R_{LL}/R_m and R_{Ls}/R_m values gives $R_t/R_m = 23$.

The resulting ratio R_t/R_t is .46. Using this value we can make a nomograph interpretation of the oil saturation of the sand if the water resistivity and the K_{rr} value are known.

This example illustrates the feasibility of the limestone curve — laterolog method in beds of medium thickness. For beds thinner than 10 ft with adjacent beds of strongly contrasting resistivities, the limestone curve can no longer be relied upon.

Other drawbacks are the fact that the limestone curve deflection is quite sensitive to hole diameter variations and rapidly loses resolution in beds of high resistivity because of its well known ceiling effect. When using the limestone curve-laterolog system, the hole size must be close to bit size or a caliper survey must be run. In beds where $R_t/R_m > 100$, the ceiling effect of the limestone curve causes the resolution of the limestone curve — laterolog interpretation to disappear.

MODIFIED LATEROLOGS

The limestone curve-laterolog combination is a somewhat unbalanced system, as its applicability is limited in all cases by the limestone curve (the laterolog has less adjacent bed effects, is fairly independent of hole diameter variations, and has no ceiling effect.

It is logical, therefore, to look for a device with an intermediate radius of investigation but with other properties comparative to those of the laterolog to take the place of the limestone curve.

The radius of investigation of a laterolog can be controlled by the extent of focusing of the central current sheet. It was shown by Doll[7] that, if the ratio of the bucking current electrode spread to the monitoring electrodes spacing is equal to 2.5 the central current sheet has boundaries which are roughly perpendicular to the axis of the sonde. The above ratio is normally referred to as "spread-ratio." If the spread-ratio is larger than 2.5, the boundaries of the central current sheet converge for some distance outward from the sonde. This makes the cross-section to current increase less rapidly with radial distance from the sonde than in the case of the current sheet with parallel boundaries and increases the radius of investigation. For spread

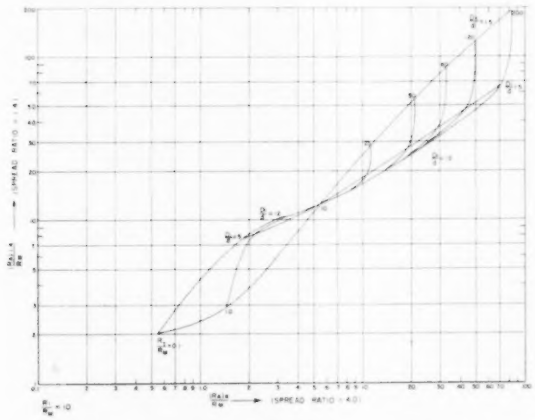

FIG. 10 — SIMPLIFIED DEFARTURE CURVE FOR LATEROLOGS OF DIFFERENT SPREAD RATIOS.

ratios smaller than 2.5, the boundaries of the current sheet diverge and the radius of investigation is smaller than in the case of the current sheet with initially parallel boundaries. Fig. 9 shows schematically the current distributions for laterolog systems with different spread ratios.

If we combine a laterolog with a spread ratio of 4.0 or larger with another arrangement with spread ratio of 2.0 or smaller, we might expect two detailed curves with essentially different current patterns from which d_i and R_t can be determined once R_i has been found from the microlaterolog. In regions of fairly low formation, resistivities (< 20 times the mud resistivity) this is indeed possible. In formations of higher resistivity, the resolution of the method vanishes rapidly. This is due to the fact that at the boreface the current lines of the central current sheet refract towards the normal (to the boreface). The larger the contrast between the formation resistivity and the mud resistivity, the stronger the refraction towards the normal. This causes the boundaries of the current sheet after refraction to become essentially parallel, regardless of whether they started out diverging or converging. If the configuration of the current sheet within the formations becomes very similar for the two devices, then we cease to have two independent equations from which we can solve for d_i and R_t.

The above behavior can be very well illustrated with the use of simplified departure curves. Fig. 10 shows a departure curve chart for a combination of a laterolog with spread-ratio of 1.4 and an arrangement with spread-ratio 4.0 for $R_i/R_m = 10$. From the two laterolog measurements, R_t/R_m can be determined with good accuracy in this case. Fig. 11 shows a chart for $R_i/R_m = 120$. We see that in this case no useful information at all regarding R_t/R_m can be obtained from the combination of two laterologs with different spread ratios.

PSEUDO LATEROLOG — LATEROLOG COMBINATIONS

The problem that remains, is to find a combination of focused resistivity logs that have characteristically different current patterns in beds of relatively high resistivities. An important step in this direction was made by the introduction of Schlumberger's pseudo-laterolog. The pseudo-laterolog has the same electrode

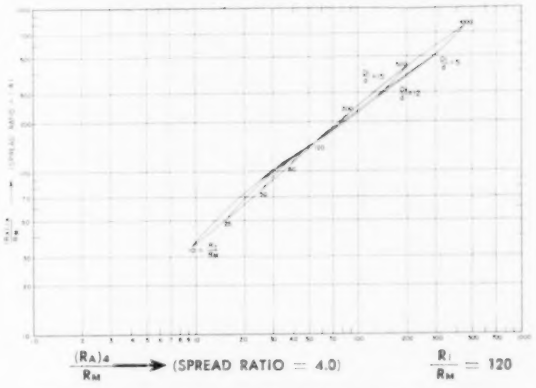

FIG. 11 — SIMPLIFIED DEPARTURE CURVE FOR LATEROLOGS OF DIFFERENT SPREAD RATIOS.

arrangement (central current electrode, monitoring span and bucking current electrodes) as the laterolog, except that the return current electrodes have been moved close to the rest of the electrode assembly. The proximity of the return current electrodes causes the bucking current to become ineffective at a short distance from the sonde. The focused current beam starts diverging at a relatively short distance beyond the boreface. Fig. 12 shows the electrode assembly and approximate current patterns of a typical pesudo-laterolog.

As a criterion of performance in high resistivity beds, we can use the resolution of the simplified departure curves for $R_i/R_m = 120$. Fig. 13 shows the departure curves for the original Schlumberger pseudo-laterolog plotted versus the standard 16-in. laterolog for $R_i/R_m = 120$. We notice that the resolution for the determination of R_t/R_m is quite good where $R_t > R_i$. When $R_t << R_i$, the resolution becomes definitely very small. Shown, also, on Fig. 13 is the electrode arrange-

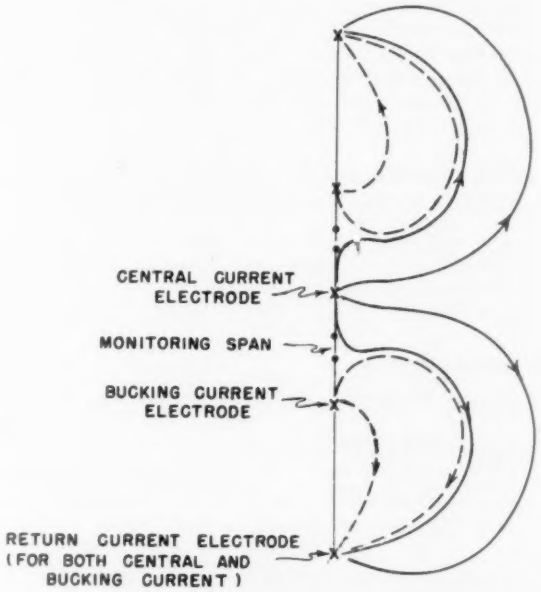
CENTRAL CURRENT ELECTRODE
MONITORING SPAN
BUCKING CURRENT ELECTRODE
RETURN CURRENT ELECTRODE (FOR BOTH CENTRAL AND BUCKING CURRENT)

FIG. 12 — ELECTRODE ASSEMBLY AND CURRENT PATTERN FOR PSEUDO-LATERGLOG.

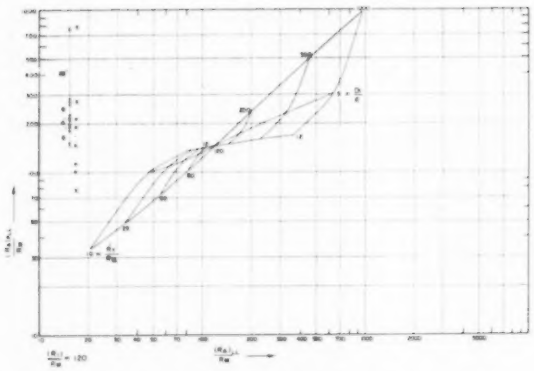

FIG. 13 — SIMPLIFIED DEPARTURE CURVE FOR PROTOTYPE PSEUDO-LATEROLOG COMBINED WITH LATEROLOG.

ment of the prototype pseudo-laterolog. One disadvantage of this arrangement is that the total spread of the central current after divergence covers a span of 96 in. This means that in thin beds the current distribution will be distorted to a considerable extent by the effects of the adjacent beds. Particularly if we have a thin conductive bed, such as a porous zone in limestone, surrounded by dense beds of high resistivity, the dense adjacent beds will limit the divergence of the central current quite drastically. Under such conditions, the departure curves calculated for infinitely thick beds no longer apply.

The best way to reduce the adjacent bed effects on the pseudo-laterolog is to make the spread and spacing as small as possible. After computations of typical departure curves for various spacings, spread ratios, and return current spreads, an experimental sonde was made combining a pseudo-laterolog with 6-in. spacing, a spread ratio of 2 and a return current spread of 28 in., with a laterolog of 6-in. spacing a 28-in. spread (spread ratio 4.67). Fig. 14 shows the electrode arrangement for this combination. Although the number of field tests of this device to date has been quite small, it is believed that satisfactory results can be obtained with it in most cases where the horizons to be analyzed are more than 5 ft thick.

FIELD EXAMPLE OF SHORT-SPACED PSEUDO LATEROLOG-LATEROLOG COMBINATION

The system of short-spaced laterolog and pseudo-laterolog curves was tried out in a section of relatively thin-bedded sandstones and shales of the Canyon formation in the West Flowers field, Stonewall County, Tex.

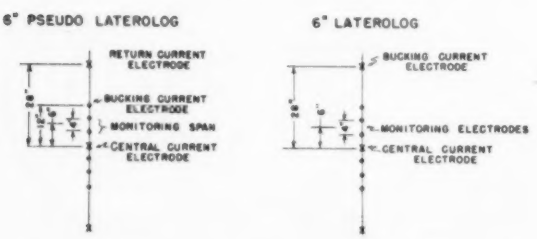

FIG. 14 — ELECTRODE ARRANGEMENT FOR MODIFIED PSEUDO-LATEROLOG AND LATEROLOG.

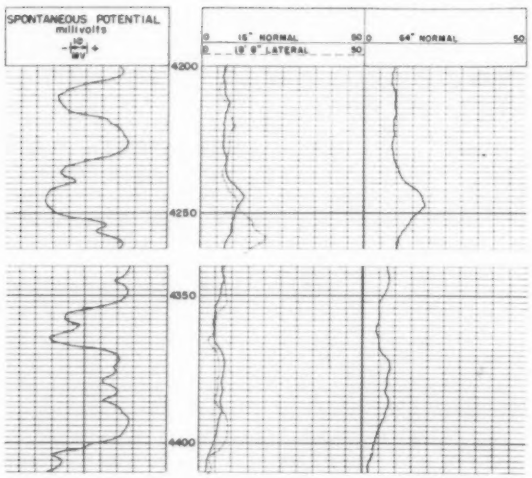

FIG. 15 — CONVENTIONAL ELECTRIC LOG, CANYON FORMATION, STONEWALL COUNTY, TEX.

Fig. 15 shows a conventional electrical log through the sections that were studied.

Figs. 16 and 17 show the microlaterolog-microlog and the laterolog-pseudo laterolog combinations through the same sections.

Invaded zone and true resistivities were determined for four zones. Assuming that the lower zone is 100 per cent water saturated, approximate water saturations for the upper two zones were calculated from Archie's formula. Table 1 gives the pertinent data of the analysis.

Fig. 18 shows the simplified departure curves for $R_t/R_m = 30$ which were used for the determination of the R_t/R_m values. The effects of the drill hole on the apparent resistivities of the laterolog and pseudo-laterolog are small enough so that we can use the chart for $R_t/R_m = 30$ for cases where R_t/R_m is approximately of that magnitude, after a proportional adjustment of the observed apparent resistivites. The adjustment is made by simply multiplying the observed apparent resistivities of the laterolog and pseudo-laterolog by the ratio of the R_t/R_m value indicated on the chart ($R_t/R_m = 30$) over the calculated R_t/R_m value. For example, the apparent resistivity ratios R_{LL}/R_m and R_{pLL}/R_m for the zone at 4,231-4,237 listed in Table 1 were multiplied by 30/27.7, and the resulting R_t/R_m is multiplied by 27.7/30.

Departure curve charts are made up for the following R_t/R_m values: 1, 5, 10, 20, 30, 50, 80, 120, 200, and

TABLE 1

Zone Feet	$R_{1\frac{1}{2}''}$	$R_{2''}$	R_{mc}	$R_{1\frac{1}{2}''}/R_{mc}$	$R_{2''}/R_{mc}$	MCT	R_{mLL}*	R_{mLL}/R_{mc}
4,402-4,406	1.5	1.95	.98	1.53	2	.6	4.7	4.8
4,362-4,366	1.5	2	.98	1.53	2.05	.6	6.0	6.1
4,353-4,358	2	2.4	.98	2.04	2.44	.37	6.8	6.95
4,231-4,237	1.9	2.4	.98	1.94	2.44	.4	7.5	7.65

Zone Feet	R_t/R_{mc}	R_t/R_m	R_{LL}*	R_{pLL}*	R_{LL}/R_m	R_{pLL}/R_m	R_t/R_m	R_t	S_w
4,402-4,406	6.8	19.6	.9	3.0	2.65	8.9	5.2	1.8	1.0
4,362-4,366	11	31.7	1.3	4.5	3.82	13.2	8.45	2.9	.79
4,353-4,358	8.5	24.5	1.45	4.7	4.26	13.8	10.3	3.5	.71
4,231-4,237	9.6	27.7	2.3	6.95	6.76	20.4	14.0	4.8	.61

*The notations R_{mLL}, R_{LL}, and R_{pLL} are used respectively for the apparent resistivities of the microlaterolog, 6-in. laterolog, and 6-in. pseudo-laterolog.

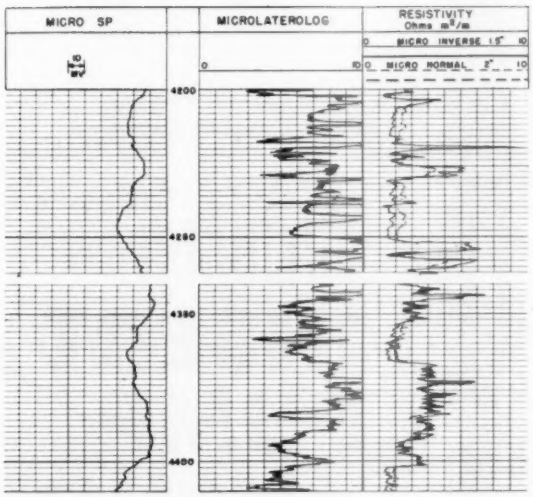

FIG. 16 — MICROLATEROLOG-MICROLOG, CANYON FORMATION, STONEWALL COUNTY, TEX.

500. The chart for the nearest R_t/R_m value to that calculated for a particular zone is selected, and the apparent resistivities are adjusted in the above manner for the determination of R_t/R_m. Graphical interpolation is used to find the R_t/R_m values corresponding to points falling between the curves on a particular chart.

In Figs. 15 through 17, the zones at 4,353-58 and 4,362-66 appear to be in the capillary transition zone at the oil-water contact and are expected to produce with a large water cut. The zone at 4,231-37 is probably at the irreducible water saturation and should produce clean oil.

CONCLUSIONS

From the work done to date, it appears to be feasible to obtain fairly accurate values of invaded bone resistivities and true resistivities in thin bedded sandstone formations by using a microlaterolog-microlog and short-spaced pseudo laterolog-laterolog combination. The resolution of the method is greatest if $R_t > R_i$. If $R_t >> R_i$, the accuracy of the method becomes very poor. For thin bed logging, it appears, therefore, advisable to keep the resistivity of the drilling mud as low as possible. In regions of very saline connate water, the mud resistivity should be held at two to four times the resistivity of the connate water, which will still make it possible to register a useful SP curve on an amplified scale. In areas of fresh connate water, we can make the mud resistivity two to four times smaller than the connate water resistivity and reverse the polarity of the SP curve.

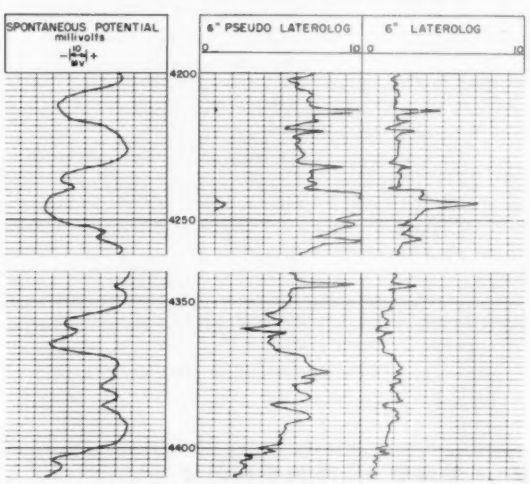

FIG. 17 — PSEUDO-LATEROLOG AND LATEROLOG, CANYON FORMATION, STONEWALL COUNTY, TEX.

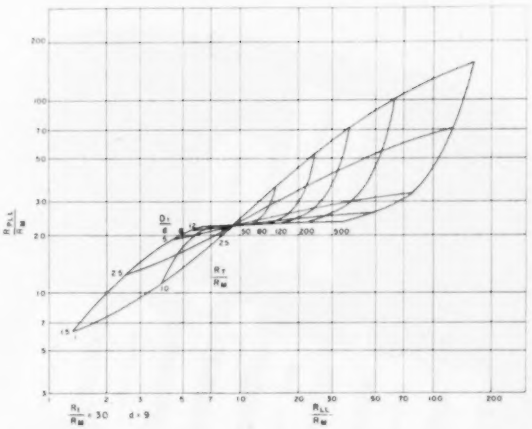

FIG. 18 — SIMPLIFIED DEPARTURE CURVES FOR 6-IN. LATEROLOG AND PSEUDO-LATEROLOG.

ACKNOWLEDGMENTS

The author wants to express his gratitude to the management of Continental Oil Co. for permission to publish this article, to Miss Elayne Chousis, Mrs. B. L. Erickson, and Miss E. A. Wells, who helped in the preparation of the simplified departure curves, and to the Engineering Department of Schlumberger Well Surveying Corp., who constructed the special laterolog-pseudo laterolog sonde and made the experimental surveys discussed in this paper.

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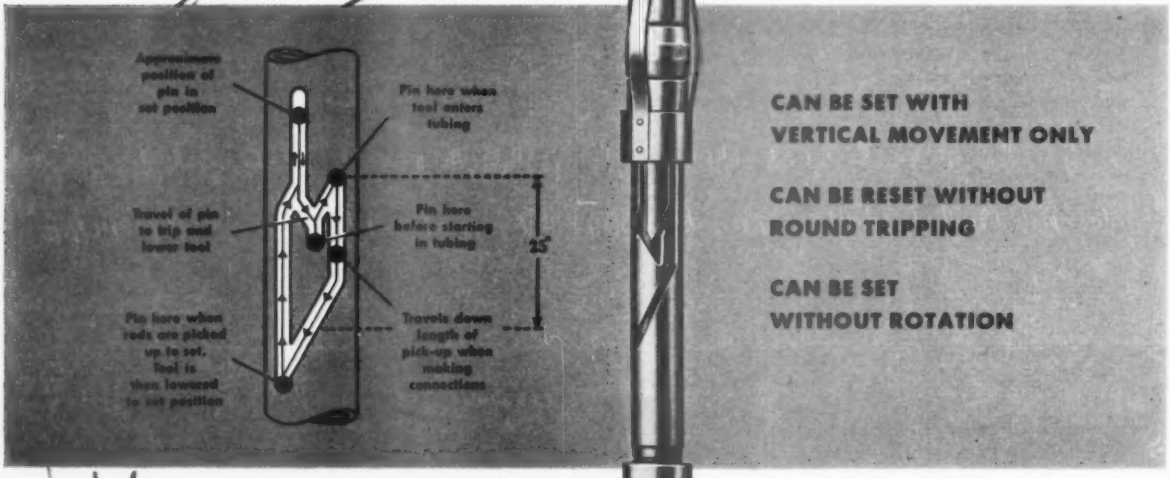
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Pin here before starting in tubing
25'
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A STUDY of DISPLACEMENTS in MICROSCOPIC CAPILLARIES

CHARLES C. TEMPLETON
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HOUSTON, TEXAS

T. P. 3804

ABSTRACT

Any explanation of the nature of multiphase fluid flow through porous media must ultimately involve a knowledge of the mechanism of such flow through the individual pores of the medium. To provide quantitative information of the latter type, a study was made of gas-liquid and liquid-liquid displacements in single uniform Pyrex capillaries with diameters as small as 4 microns.

Quantitative observation of air-liquid displacements with zero contact angle indicates the adequacy of a model based on Poiseuille's Law and the independence of capillary pressure and interfacial velocity. Consequently, this work discounts previous claims that flow is abnormally retarded in very small capillaries.

For the displacement of a very viscous oil by water in a capillary initially filled with water, flow is faster than predicted by the above model. This behavior is probably due to the existence of a thin annular film of water between the oil column and the capillary wall as postulated by Yuster.

INTRODUCTION

The need for experimental observation of the microscopic nature of multiphase fluid flow, to further the understanding of the results of macroscopic flow investigations, has been previously recognized. Chatenever and Calhoun[1] in connection with the API Project 47B have extensively studied the flow of fluids through layers of glass or lucite spheres between glass or lucite plates. Lowman[2] prepared an interesting film concerning flow in a single capillary, using an apparatus which made a moving interface appear stationary in the field of a microscope.

The purpose of the present investigation was to determine what contribution might be made to this field by comprehensive *quantitative* observation of gas-liquid and liquid-liquid displacements in single capillaries of uniform, very small diameter. The techniques used are similar to those of Lowman but incorporate improvements necessary for quantitative work. Quantitative observations must begin with fluids of simple chemical composition to provide a basis for analyzing the more complex behavior that may be expected with natural reservoir fluids. However, some qualitative observations on systems involving crude oils are presented.

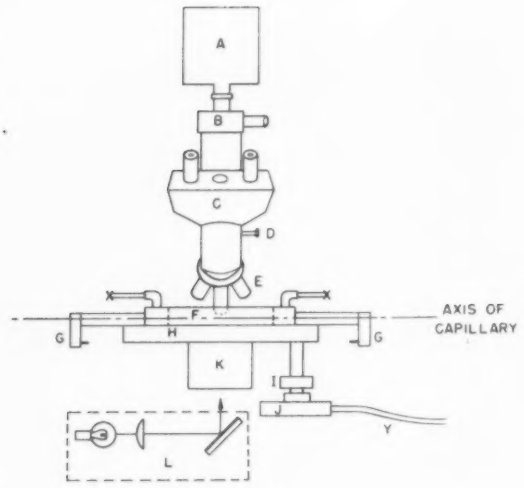
Experiments of this sort involve the observation of the velocity of the interface separating two fluids, and have been performed in horizontal or vertical capillaries by several investigators.[3,4,5,6,7,8] The most general treatment of their mechanics, by Brittin,[9] involves forces due to capillarity, viscous resistance, gravity, an "end-drag" effect, and the rate of change of momentum of the capillary contents.

Since the range of pore diameters of interest in petroleum reservoirs is about 0.1 to 100 microns, it was desired to perform these experiments in the smallest capillaries possible, to ascertain whether capillary diameter had any effect on the existing theory based on data from larger capillaries.* It was also important to be able more systematically to vary the direction and rate of displacement than was done by previous investigators. Finally, to concentrate attention on viscous and capillary forces by eliminating gravity as a parameter, this study involves only horizontal capillaries. The work of Eley and Pepper[7] with a "large" (0.766-mm diameter) horizontal capillary is the previous investigation which is most similar to the present method of quantitative observation. Here capillaries with diameters as small as 4 microns will be studied.

[1]References given at end of paper.

Manuscript received in the Petroleum Branch office July 31, 1953. Paper presented at the Petroleum Branch Fall Meeting in Dallas Oct. 19-21, 1953.

*Even single-phase flow in very small capillaries has not been investigated as extensively as one might imagine from the universal acceptance of Poiseuille's law. Bingham,[10] in reproducing Poiseuille's data, indicates that only five measurements were made in capillaries of about 13 microns diameter, and that the other capillaries had bores of 29 microns or greater. The most comprehensive study was that of Bulkley,[11] who used glass capillaries of about 11 microns diameter.



LEGEND

A — CAMERA
B — BEAM SPLITTER
C — BINOCULAR HEAD
D — SLIDE FOR QUICK-SHIFT BETWEEN BINOCULAR AND CAMERA-BEAM SPLITTER SYSTEMS
E — OBJECTIVES
F — CELL CONTAINING CAPILLARY
G — LIMIT MICROSWITCHES AND CELL HOLDER
H — MECHANICAL STAGE
I — MANUAL KNOB FOR STAGE MOVEMENT PERPENDICULAR TO PLANE OF ILLUSTRATION
J — GEARED DRIVE FOR STAGE MOVEMENT ALONG AXIS OF CAPILLARY
K — CONDENSER
L — BUILT-IN ILLUMINATION SYSTEM
X — FLEXIBLE HOSE CONNECTIONS TO PRESSURE SYSTEM
Y — FLEXIBLE SHAFT TO MOTOR DRIVE UNIT

FIG. 1 — GENERAL ARRANGEMENT OF APPARATUS.

APPARATUS AND TECHNIQUES

The general arrangement of the Leitz Ortholux microscope and its associated apparatus is sketched in Fig. 1.

Fig. 2 illustrates the capillary cell (Type 1) used in the first several months of the study. The lower stainless steel block at each end contains a fluid reservoir and an inclined hole to receive the end of the capillary. Since the capillary is sealed to the block only at the external end of the hole, the fluid contacts glass and steel but no cementing material. The upper steel block receives a brass elbow which permits connection to a pressure system employing Nullmatic regulators. A pressure-tight seal is obtained by placing a rubber gasket between the two blocks and screwing them together. Only one block has pressure applied to it at any one time; the other is always at atmospheric pressure. Either mercury or oil manometers were used.

About an hour is required for mounting a capillary in the cell. The end-blocks are cleaned with boiling ethanol and dried. A section of capillary (about 12 cm long) is cut; its length is measured with the aid of a stereoscopic microscope. A reference mark is placed on the capillary with fingernail polish, and its location measured with respect to the ends. This allows subsequent calibration of a Veeder-Root counter (geared to the stage-drive) in terms of capillary position for any given run. The capillary is inserted into both end-blocks, and is fastened down in a straight position on the bottom plate with small pieces of drafting tape. Dekhotinsky cement or paraffin is then used to make a dam around the capillary and to seal the capillary gas-tight into the end blocks. The pool surrounding the capillary is filled with immersion oil.

With the Type I cell, no provision was made for temperature control; the temperature of each displacement was read from a thermometer mounted on the mechanical stage. On the basis of some auxiliary measurements with a thermocouple, it was concluded that the true temperature of the capillary was known within $\pm$ 0.1°C.

During the later part of the study a new cell (Type II) was used, in which the temperature could be maintained at 30.00° $\pm$ 0.1°C. This cell differs from the Type I cell only in having a hollow set of all-metal cell walls for the circulation of thermostated water.

The capillaries were prepared from Pyrex glass by an apparatus developed in conjunction with this study.[13] It employs a modification of the method of Shereshefsky[14] with the replacement of gas heating by electrical heating. Capillaries are drawn immediately before mounting to keep them as clean as possible. Before drawing, the tubing stock is cleaned with acid-dichromate solution, rinsed with distilled water, baked dry, and sealed to permit storage.

Diameters of capillaries are measured with a 12.5 $\times$ filar micrometer eyepiece. By taking the average of seven to 10 measurements, a length may be determined to $\pm$ 0.1 μ with a 22 $\times$ oil-immersion objective. The use of immersion oil removes the necessity of applying corrections to these measurements.[14]

QUALITATIVE EXPERIMENTS

The appearance of oil-water-Pyrex systems under the microscope depends on the refraction indexes involved. Air slugs are quite dark, water slugs somewhat lighter, and oil slugs are clear. Boundaries of oil against glass are practically invisible, but boundaries of water against glass are quite sharp. A water torus (doughnut) was observed to be a fairly stable configuration.

It was established early that velocities of the order of 1 cm/min (46.2 ft/day), which exceed the range to be expected in a reservoir except perhaps near the well, do not in general lead to appreciable interfacial deformation in *freshly prepared* systems. In a 30-micron-diameter capillary, a water-air interface had the same geometry at rest and traveling at 3 cm/min as did a water-refined hydrocarbon fraction interface at rest and moving at 2 cm/min. In a latter part of this paper photographic measurements show that for fresh Pyrex-air-liquid systems in which the static contact angle is zero the static and dynamic angles are the same to within 1 per cent in cos Θ. Photographic measurements on a Pyrex-air-methylene iodide system showed the range of hysteresis to be about 7 per cent of the cosine of the static angle (Θ° = 52°).

Most of the air-liquid systems observed did not change their behavior very rapidly upon aging over a few days. However, the behavior of liquid-liquid systems tended to become considerably more complicated after aging, the situation being more involved for mixtures than for pure liquids. Thus, when alternate slugs of distilled water and a mixed "oil" (90 per cent kerosene, 10 per

cent α-monochloronapthalene) were set in motion, the advancing end of the water slug flattended in agreement with the conventional pattern of contact angle hysteresis.[15]

Crude-oil samples from several fields were displaced with water. For each crude, a single crude-water interface was created in a 5-micron-diameter capillary, which had initially been filled with water. The interface was immediately displaced in each direction at about 1 cm/min. If the interface was initially stable, it was then maintained as nearly as possible at a fixed position in the capillary for about 3 hours, by continual adjustment of the applied pressure. The "aged" interface was then displaced in each direction at 1 cm/min. for another check on its stability.

Some of the crude-oil-water systems examined showed a 15 to 20 per cent decrease in capillary pressure over a 3-hour period. When this occurred for a Benton field, Illinois crude which had been exposed to the atmosphere for 6 months, it was thought to indicate the presence of surface-active agents formed by oxidation. However, the decline also was observed for a fresh crude sample from the KMA field, Wichita County, Tex.

As for interfacial instability, crude-water interfaces broke up during the initial displacements for fresh sample from the Luke field, Okla., and the Fox-Graham field, Okla. The Benton field, Ill., crude interface with water showed instability only after the 3-hour aging period. The crude-water interfaces for fresh samples from the Mercy field, Tex., and the KMA field, Tex., showed no appreciable instability during the entire test. Displacements at comparable velocities of water-oil interfaces for some pure hydrocarbons and some refined hydrocarbon mixtures, covering a viscosity range from 0.6 to 12 cp, have not revealed interfacial instability. All the crudes had velocities within this range at the temperature of the observations. Thus, the effect appears to be more dependent upon the chemical nature of the fluids rather than upon their physical properties.

The interfacial break-up always followed a characteristic pattern, which is illustrated in Fig. 3. It has been observed only when water displaces oil. As the water-oil interface begins to move, the center part of the interface tends to lag as in Fig. 3-b. Soon the wetting phase begins to advance along the wall on one or both sides, giving the situations shown in Fig. 3 (c, d, e). As soon as flow stops, the distorted interfacial region readjusts into slugs and tori.

Fig. 4 describes an air displacement of Benton crude, followed by a water flood, which allows an estimate of the thickness of the oil film left on the wall during the displacement of the oil by air. An air slug separated water and crude columns in a 36.7-micron-diameter capillary as indicated in Fig. 4-a. The capillary had been initially filled with water. Photographs of the water-air and air-oil interfaces at rest are shown, respectively, in Fig. 4 (b and c). During the initial entry of the oil there was no change in the appearance of the air-oil interface.

However, when the direction of displacement was reversed, after a time the water-air interface changed into a combination of water-oil interface and an oil-air interface (Fig. 4-d). This apparently indicated that an oil film was left behind the air-oil interface, and that this film was collected into an oil slug by the advancing water-air interface. (Because the capillary was initially filled with water, there probably was also a water film between the oil film and the wall.) After the air slug had traveled farther, the oil slug disintegrated into the situation portrayed in Fig. 4-e. Here there is essentially a water-air interface with an oil "sack" attached to it. As displacement continued, additional oil was apparently picked up from the wall, causing the oil "sack" to grow into the "sausage" shown in Fig. 4-f. From the distances traveled and the dimensions of the capillary, it was estimated that the thickness of the oil film was about 0.012 micron. The complex shape of the oil "sack" suggests rigid film formation, which has been observed at crude-oil-water interfaces with aging.[16]

QUANTITATIVE OBSERVATION OF DISPLACEMENTS

Definitions and Theory

Consider a horizontal capillary of length l and of uniform radius r, containing a wetting-phase column (fluid 1) separated by a single interface from a nonwetting-phase column (fluid 2). The viscosities are μ_1 and μ_2. x is the length of capillary occupied by wetting phase; $l-x$ is occupied by the nonwetting phase. $v = dx/dt$ is the velocity of the interface.

P_c is the pressure at the nonwetting phase end of the capillary minus that at the wetting phase end. P_c is the capillary pressure. P_c°, the static capillary pressure, is equal to the particular value of P_c that maintains the interface stationary. θ and θ° are the dynamic and static contact angles, respectively.

From the fundamental equation of capillarity,

$$P_c = \frac{2\gamma \cos \theta}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where γ is the interfacial tension for a liquid-liquid system, or the surface tension for an air-liquid system.

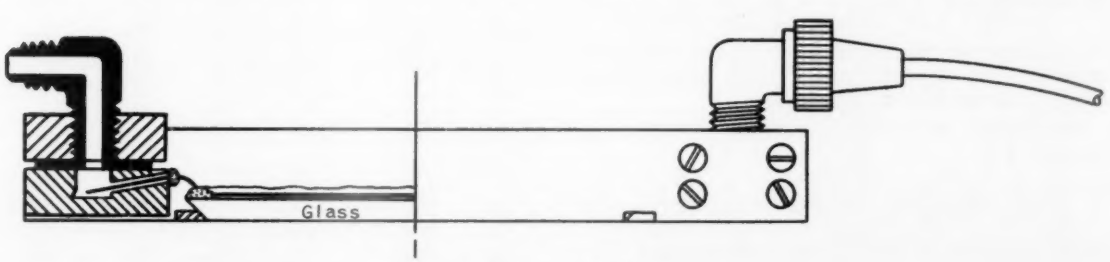


Fig. 2 — Capillary Cell, Type 1.

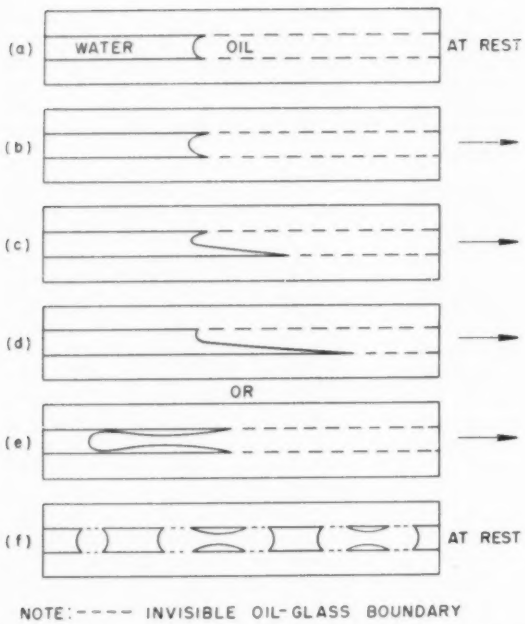


FIG. 3 — MECHANISM OF BREAK-UP OF A WATER-OIL INTERFACE DURING A WATER FLOOD.

Let a "boundary tension" be defined as

$$T = \frac{P_c \cdot r}{2} = \gamma \cos \Theta \, , \, . \, . \, . \, . \, . \, . \, . \quad (2)$$

for the expression of both static (T°) and dynamic (T) results.

The following assumptions will be made for evaluating the data: (1) Poiseuille flow, since the Reynolds numbers are low. (2) The fluids are incompressible. (3) Displacement is perfect at the interface. (4) Capillary hysteresis is absent; i.e., $P_c = P^\circ_c$, since in any of the systems to be studied, the static, advancing, and receding contact angles appeared to be identical to within 1 per cent in cos Θ. From the above it may be shown that

$$P^\circ_c - P_i = [8v_i/r^2] \, [(\mu_{1eff} - \mu_{2eff}) \, x + \mu_{2eff} \cdot l] \, , \quad (3)$$

where the subscripts distinguish effective viscosities determined from displacement data from the values determined in conventional viscometers (μ_1 and μ_2).

P_i is maintained constant during a displacement. Measurements are made of the times t at which the interface passes certain positions x. When possible, photographs are made of the interface, both stationary and moving, for the measurement of Θ and Θ°. Velocity values are calculated from the observed (x,t) data by the approximation of setting $v = (x_1 - x_i)/(t_1 - t_i)$ at $x = (x_1 + x_i)/2$. P°_c is measured with the interface at various points. The surface or interfacial tensions of the fluids are measured either by the pendent-drop apparatus or the duNouy tensiometer.

All quantities in Equation (3) are known except μ_{1eff} and μ_{2eff}. Let

$$G = \left(\frac{r^2}{8}\right) (P^\circ_c - P_i) \, , \, . \, . \, . \, . \, . \, . \, . \quad (4)$$

which is constant for a given displacement; then

$$G/v = (\mu_{1eff} - \mu_{2eff}) \, x + \mu_{2eff} \cdot l \quad . \, . \, . \, . \, . \quad (5)$$

Hence a plot of G/v versus x should be linear, and μ_{1eff} and μ_{2eff} can be determined from the slope and intercept. When either viscosity gets much greater than the other, the smaller effective viscosity is subject to a large propagated error in this graphical method. Thus for an air-liquid displacement the handbook value of air viscosity is substituted for μ_{2eff} in Equation (3), and a value of μ_{1eff} can be calculated numerically from each (x, t, v) point.

LIQUIDS USED IN QUANTITATIVE EXPERIMENTS

Distilled water was used in these displacements. The benzene (Baker) was C.P. grade, the *n-cetane* (Du Pont) was "practical" grade or better. Nujol (heavy mineral oil, U.S.P.) was sold by Stanco, Inc. Refined hydrocarbon "Cut No. 3" was a mixture of 65 per cent from a boiling range of 356°-405° and 35 per cent from a boiling range of 391°-477°C.

RESULTS FOR AIR-LIQUID DISPLACEMENTS IN 25 TO 35 MICRON INNER DIAMETER CAPILLARIES

Table 1 presents typical data gathered from the application of these methods to displacements in Pyrex capillaries with inner diameters between 25 and 35 microns. With water and two refined hydrocarbon fractions (Cut No. 3 and Nujol), the viscosities range from about 1 to 140 cp. Each capillary is assigned a number; each displacement in that capillary is designated by adding a letter.

TABLE 1 — TYPICAL AIR-LIQUID DISPLACEMENTS; 25- TO 35-MICRON I.D. (TYPE II CELL IF MARKED WITH ASTERISK; OTHERWISE TYPE I CELL)

A. Constants and Static Behavior

Run No.	Capillary Diameter cm	Surface Tension γ dynes/cm	$\frac{T^\circ}{\gamma}$	cos Θ° (From Photographs)
Water				
37A,B	28.65×10^{-4}	71.82	.991	0.99
Refined Hydrocarbon Cut No. 3				
36A,B,C	29.52	31.2	.979	1.00
*44A,B,C,D	29.98	30.76	1.026	.99
*45A,B,C,D	29.20	30.76	.997	.99
Nujol				
*42A,B,C,D,	31.37	31.6	.959	1.00
*43A,B,C,D	31.64	31.15	.984	.98
*46A,B,C,D	28.17	31.15	1.008	1.00

B. Dynamic Behavior

Run No.	Temperature °C	$(P^\circ_c - P_i)/P^\circ_c$	cos Θ (From Photographs)	μ_i poise	μ_{1eff}/μ_1
Water					
37A	25.90	− .051	0.99	.00876	.977
37B	25.85	.050	.99	.00877	1.124
Refined Hydrocarbon Cut No. 3					
36A	24.60	5.348	1.00	.479	.981
36B	24.71	−4.775	1.00	.476	.960
36C	24.89	5.173	1.00	.471	.958
*44A	30.00	−6.872	.99	.364	.984
*44B	30.00	7.298	.98	.364	1.029
*44C	30.00	−5.298	.96	.364	.992
*44D	30.00	9.423		.364	1.031
*45A	30.00	−3.065	.99	.364	1.062
*45B	30.00	5.105	.98	.364	1.020
*45C	30.00	−5.140		.364	1.059
*45D	30.00	7.143	.98	.364	1.055
Nujol					
*42A	27.40	−8.249	1.00	1.237	1.058
*42B	27.40	10.327	1.00	1.237	1.059
*42C	27.40	−9.293	1.00	1.237	1.054
*42D	27.40	13.008	1.00	1.237	1.047
*43A	30.07	10.146	.99	1.048	.996
*43B	30.09	−8.068	.99	1.046	.967
*43C	30.09	11.255	.99	1.046	.965
*43D	30.09	−9.255	.99	1.046	.944
*46A	30.00	−4.314	1.00	1.055	1.044
*46B	30.00	6.345	1.00	1.055	1.050
*46C	30.00	−5.484	1.00	1.055	1.028
*46D	30.00	7.468	1.00	1.055	1.043

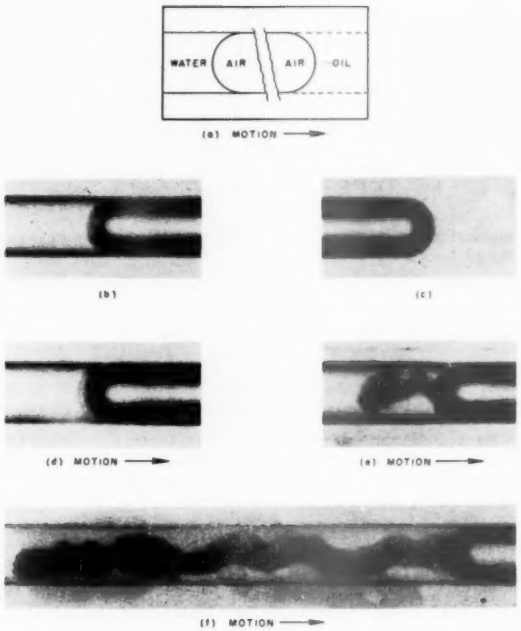


FIG. 4 — AIR DISPLACEMENT OF BENTON CRUDE FOLLOWED BY WATER FLOOD WHICH COLLECTS OIL FILM FROM WALL.

In three-fourths of the air-liquid systems studied, P_c° along the capillary for each case was constant to within ± 1 per cent of the average value. For any run, P_c° has been taken as the average of the values at the ends of all the runs in the particular capillary.

Part *A* of Table 1 summarizes the static behavior as value of T°/γ; values of cos Θ° obtained from enlarged photographs are given in the final column. The actual agreement may be judged from the fact that the average of the T°/γ values is 0.992, while that of the actual cos Θ° entries is 0.993.

Part *B* of Table 1 describes the dynamic observations. The quantity $(P_c^\circ - P_t)/P_c^\circ$ seems to be the most convenient means for representing the magnitude of the forces and pressures involved. If $P_c^\circ = P_c$, then this pressure ratio is equal to the ratio of viscous pressure (work) to capillary pressure (work). Further, the ratio is positive for a wetting-phase flood and negative for a nonwetting-phase flood.

The first result to be noted is that the static and dynamic contact angles have been experimentally shown to be the same, and equal to zero, within a reasonable experimental error. This was the basis for assuming that $P_c = P_c^\circ$ in the theoretical discussion, although this equality also requires that γ be unchanged by interfacial motion.

If the model adequately describes the experimental behavior, then $\mu_{t\,eff}/\mu_t$ is expected to be unity. Actually, the average of the $\mu_{t\,eff}/\mu_t$ values in Table 1 is 1.019. Although the extreme values are 0.944 and 1.124, the average deviation from the mean is only 0.038. A study of Table 1, Part *B* will show that there is no apparent systematic relation between $\mu_{t\,eff}/\mu_t$ and any of the following:

1) the direction of displacement or sign of $(P_c^\circ - P_t)/P_c^\circ$;

2) the ratio of viscous pressure to capillary pressure [magnitude of $(P_c^\circ - P_t)/P_c^\circ$];

3) the liquid viscosity; or

4) the surface tension.

Hence we may conclude that our model is adequate for describing air-liquid displacements, in capillaries of 30 microns inner diameter, within a random error of about ± 4 per cent.

RESULTS FOR AIR-LIQUID DISPLACEMENTS IN 3 TO 7 MICRON INNER DIAMETER CAPILLARIES

Table 2 describes 12 runs in the Type II cell for three capillaries, with diameters between 6 and 7 microns with a refined hydrocarbon fraction of about 36 cp viscosity. Here the T°/γ values average 0.958; no direct photographic measurement of cos Θ° was feasible in capillaries this small. The $\mu_{t\,eff}/\mu_t$ values average 1.007, with an average deviation from the mean of 0.065. This average dynamic behavior is very close to what was theoretically expected.

The present techniques were also applied to five other liquids in capillaries whose diameters were between 3 and 7 microns in the Type I cell. The viscosities of these liquids ranged from 0.6 to 160 cp. A total of 26 air-liquid displacements in nine different capillaries was observed. For these data, T°/γ averaged 0.957, while the average of $\mu_{t\,eff}/\mu_t$ was 0.930. Even though $\mu_{t\,eff}/\mu_t$ was somewhat lower than expected (these measurements were made in the beginning of the study when the techniques may not have been fully developed), these data nonetheless demonstrated the lack of any systematic relation between $\mu_{t\,eff}/\mu_t$ and $(P_c^\circ - P_t)/P_c^\circ$, μ_t, or γ in these smaller capillaries. For later comparison with water-Nujol results, it should be stated that four air-Nujol displacements in two capillaries (with diameters of 4.99 and 5.52 microns, respectively) gave an average $\mu_{t\,eff}/\mu_t$ of 0.935 ± 0.009.

Bulkley[11] investigated the flow of several liquids in glass capillaries of about 11 microns inner diameter.

TABLE 2 — AIR-OIL DISPLACEMENTS, 6- to 7-MICRON I.D., TYPE II CELL. OIL IS "REFINED HYDROCARBON CUT NO. 3."

A. Constants and Static Behavior

Run No.	Capillary Diameter cm	Surface Tension γ dynes/cm	$\frac{T^\circ}{\gamma}$
47A,B,C,D	6.177×10^{-4}	30.76	0.963
49A,C,D,F	6.370	30.76	.937
50A,B,C,D	6.604	30.76	.975

B. Dynamic Behavior (All runs at 30.00°C; $\mu_t = 0.3642$ poise)

Run No.	$(P_c^\circ - P_t)/P_c^\circ$	$\mu_{t\,eff}/\mu_t$
47A	−5.907	1.063
47B	7.907	1.060
47C	−6.943	1.053
47D	8.943	1.061
49A	−6.683	.909
49C	−7.595	.913
49D	2.803	.916
49F	2.841	.921
50A	−6.991	1.123
50B	9.024	1.070
50C	−7.729	1.001
50D	9.707	.994

From his flow data and the conventionally measured viscosities of the fluids, he calculated radius values which he compared with radius values measured according to the visual technique of Shereshefsky.[17] The average of his visual values, for a given capillary, was 2.1 per cent lower than the average of his calculated values; i.e., flow was faster than indicated by the visually measured radius and the viscosity. Bulkley concluded that the effects are within the range of experimental error. The recent claims of Henniker[17,18] that flow in very small capillaries is slower than predicted by Poiseuille's law and conventionally measured viscosities has been effectively rebutted by Bulkley.[19]

From Equation (3) it may be seen that, when μ_{2eff} is much less than μ_{1eff}, μ_{1eff} is proportional to r^2. T° is directly proportional to r from Equation (2). If for Table 2 all the deviations of μ_{1eff}/μ_1 from unity were attributed to a mistake in the visual radius measurement (which seems possible because of the approximate agreement between μ_{1eff}/μ_1 values for runs in a given capillary), the following errors in r result:

	Systematic	Random
Static (T°/γ)	−4%	±2%
Dynamic (μ_{1eff}/μ_1)	<1%	±4%

Since Bulkley's results could have been caused by a −2.1 per cent systematic error in the visual diameter measurement technique, such an error might be inherent in this method.

These quantitative measurements cover only cases for which the air-liquid-solid contact angle is zero. It appears that this angle is zero for water or simple hydrocarbon mixtures. The techniques might well be applied to systems such as air-methylene iodide-Pyrex for which this angle is greater than zero.

QUANTITATIVE STUDY OF OIL-WATER DISPLACEMENTS

The results of a study of oil-water displacements will almost certainly be affected by whether the capillary is initially filled with oil or water. A few results will now be presented for the "water-in-first" case. If these data are interpreted according to the present theory ($P_c = P_c^\circ$), oils of high viscosity show μ_{eff}/μ values definitely less than unity. The same oils gave μ_{eff}/μ values of about unity for the air-oil case. Thus Table 3 contrasts the results obtained with the Type I cell for the benzene-water and Nujol-water systems in Pyrex capillaries with diameters between 4 and 6 microns. Here the effective viscosities of both water and oil have been determined by the graphical method. For these water-oil systems P_c° in a given capillary was generally constant to about ±2 per cent, rather than the ±1 per cent range encountered in air-liquid systems.

In 5-micron-diameter capillaries, the only evidence for the assumption of $P_c = P^\circ$ is that the contact angle *visually* appeared to be the same during oil and water floods, and that the interface remained stationary at a well-defined static capillary pressure. However, photographic measurements of the dynamic and static contact angles for the same oil-water systems in 30-micron-diameter capillaries show that $\theta = \theta^\circ$ within 1 per cent of the cosine.

For the benzene-water case, only ranges or average values of the various quantities have been recorded. Within an average deviation of about 10 per cent, our model seems to describe water-oil displacements adequately when the capillary is initially filled with the wetting liquid and the viscosities of the two liquids are not greatly different.

In the Nujol-water case it may be stated that the wide variation of the μ_{1eff}/μ_1 values has little physical significance because, when $\mu_1 << \mu_2$, μ_{1eff} is affected greatly by small errors in the measured quantities. In fact, if μ_{1eff} is set equal to μ_1 and μ_{2eff} is calculated numerically, all the μ_{2eff}/μ_2 values still remain between 0.486 and 0.613. Gillespie,[20] in studying slug flow in the water-castor oil system in 40 to 60 micron-diameter capillaries, observed the equivalent of these low effective viscosities for the oil phase.

The interpretation of the reduced μ_{2eff}/μ_2 values is that there is probably a thin annular film of water between the oil column and the capillary wall. Yuster[21] has derived an expression for the relative permeabilities in a uniform capillary in which this distribution of fluids prevails. His Equation (24) for the relative permeability to oil, with our notation for the viscosities, is

$$K_{ro} = 2S_o(1-S_o)\frac{\mu_2}{\mu_1} + S_o^2, \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where S_o is the oil saturation. If ϵ is the ratio of the thickness of the water film to the radius of the capillary, then

$$S_o = \frac{\pi(r-\epsilon r)^2}{\pi r^2} = (1-\epsilon)^2 \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Further, it may be shown* that

$$K_{ro} = (\mu_2/\mu_{2eff})(1-\epsilon)^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

By combining Equations (6), (7), and (8), we obtain

$$\frac{\mu_2}{\mu_{2eff}} = 2\epsilon(2-\epsilon)\frac{\mu_2}{\mu_1} + (1-\epsilon)^2 \quad . \quad . \quad . \quad (9)$$

If Equation (9) is applied to the Nujol data of Table 3, the calculated water-film thicknesses all lie between 28 and 44 Å. These values are reasonable both in terms of molecular dimensions and the limit of resolution of the microscope.

It should be emphasized that, although these results

TABLE 3 — OIL-WATER DISPLACEMENTS (TYPE I CELL)
"WATER-IN-FIRST"

Run No.	$\frac{P_{c^\circ} - P_{c}}{P_{c^\circ}}$	$\frac{\mu_2}{\mu_1}$	(Water) (μ_{1eff}/μ_1)	(Oil) (μ_{2eff}/μ_2)
Benzene-Water				
29 runs in eight capillaries	Range: −0.609 to 0.632	Range: 0.665 to 0.681	Avg.: 0.997 Avg. Dev.: ±.105	Avg.: 0.939 Avg. Dev.: ±.092
Nujol-Water				
10A	3.452	165.	1.12	.485
10B	−3.081	155.	4.07	.477
13A	3.912	176.	−.56	.493
13B	−3.728	176.	−.55	.530
14A	3.548	173.	7.89	.566
14B	−3.136	173.	12.02	.550

Capillary Diameters:

Benzene-Water	Range:	4.42×10^{-4} to 6.16×10^{-4} cm
Nujol-Water	10A-B	4.97×10^{-4} cm
	13A-B	5.79
	14A-B	5.16

*K_{ro} is the ratio of the actual oil flow rate during the displacement, Q_{actual}, to the flow rate to be expected in the same capillary when *completely* filled with oil, Q, with the same potential gradient (dP/dx) in both cases. By Poiseuille's law: $Q = (\pi r^4/8\mu_2)(dP/dx)$. Further, $Q_{actual} = \pi r^2(1-\epsilon)^2 v$, where v is the interfacial velocity. Our calculations essentially define μ_{2eff} by the relation $dp/dx = 8v\mu_{2eff}/r^2$. Combination of these relationships yields Equation (8).

confirm the possibility of a relative permeability to oil greater than unity for *the case of a uniform capillary*, they in no way prove the existence of such an effect in actual cores. At most they might suggest the possibility of its occurrence in a core. However, most flow data rule against this possibility. There might be value nonetheless in more extensive checking of the generally accepted independence of relative permeability and viscosity in oil-water systems with oil viscosities of several poises.

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MEET the AUTHORS

J. S. Aronofsky

Magnolia Petroleum Company's Julius Aronofsky is senior research engineer at their Field Research Laboratories. He has a BS degree from Southern Methodist University, a MS degree from Stevens Institute, and a PhD from the University of Pittsburgh.

L. de Witte

Since 1951 Leendert de Witte has been with Continental Oil Co., and he is now in charge of the physics sections of their Production Research Division. He was born in Bergen op Zoom, Holland, in 1925, and came to the U. S. in 1946, after completing geological studies at the University of Groningen and serving in the Royal Netherlands East Indies Army. He received his MS and PhD in geophysics from California Tech.

☆

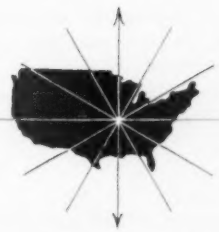
R. Jenkins

The senior research technologist at Magnolia's Field Research Laboratories is Rodman Jenkins, who has been with the company since 1949. He was formerly with E. I. DuPont de Nemours & Co., and holds a BS degree from Massachusetts Institute of Technology, MChE from the University of Delaware, and PhD from California Tech.

☆

C. C. Templeton

The senior research chemist at Shell Development Company's Exploration and Production Research Division in Houston, Charles C. Templeton, has been with the company since 1950. He holds a BS from Louisiana Tech and a PhD in physical chemistry from the University of Wisconsin. The 1952 recipient of the Turner Prize of the Electrochemical Society formerly instructed at the University of Michigan.



TENTATIVE PROGRAM of PAPERS and ACTIVITIES for PETROLEUM BRANCH FALL MEETING in SAN ANTONIO

(All papers shown are subject to change or withdrawal)

Sunday, October 17

1:00 p.m. to 6:00 p.m. — ADVANCE REGISTRATION — Ballroom, Plaza Hotel

2:00 p.m. to 5:00 p.m. — PETROLEUM SECTION CONFERENCE — Roof Garden, Plaza Hotel, Kenneth B. Ford, Conference Chairman, Presiding

Monday, October 18

8:00 a.m. to 5:00 p.m. — REGISTRATION AND EXHIBITS — Ballroom, Plaza Hotel

9:00 a.m. to 11:15 a.m. — FIELD CASE HISTORIES — Roof Garden, Plaza Hotel

378-G: *Case History of Reservoir Performance of a Highly Volatile Type Reservoir,* by REX W. WOODS, Consulting Engineer, Tulsa, Okla.

379-G: *A Study of the West Cement Medrano Unit — Caddo County, Oklahoma,* by ALVIN E. HALL, Phillips Petroleum Co.

380-G: *Pressure Maintenance by Inert Gas Injection at Elk Basin,* by D. L. GARTHWAITE, FLOYD KREBILL, and F. M. STEWART, Stanolind Oil and Gas Co.

9:00 a.m. to 11:30 a.m. — LOGGING — Ballroom, Gunter Hotel

400-G: *A Subsurface Flowmeter,* by R. C. RUMBLE, Humble Oil and Refining Co.

401-G: *A Method for Neutron-Derived Porosity for Thin Beds,* by J. M. EDWARDS and A. L. SIMPSON, McCullough Tool Co.

402-G: *A Study of Electric Log Interpretation Methods in Shaly Formations,* by LEENDERT DE WITTE, Continental Oil Co.

403-G: *Digital Computing Machines as a Tool for Obtaining Subsurface Correlations from Electric Logs,* by R. K. GUTHRIE and R. H. WALLACE, Seeligson Engineering Committee.

10:00 a.m. to 12:00 m. — For the Ladies — WELCOMING COFFEE — Brackenridge Park

12:15 p.m. — PETROLEUM BRANCH WELCOMING LUNCHEON — Roof Garden, Plaza Hotel, Paul R. Turnbull, Luncheon Chairman, Presiding

2:30 p.m. to 5:00 p.m. — LABORATORY METHODS — Ballroom, Gunter Hotel

408-G: *Effect of Aging of East Texas Cores on Results of Laboratory Determinations,* by J. S. OSOBA, Humble Oil and Refining Co.

409-G: *A Study of Water Flood Efficiency in Oil-Wet Systems,* by J. E. WARREN and JOHN C. CALHOUN, JR., The Pennsylvania State University.

410-G: *Effects of Pressure Decline Rate and Fluid Characteristics on Solution Gas Drive Performance of Heterogeneous Limestones,* by C. R. STEWART, E. B. HUNT, JR., F. N. SCHNEIDER, T. M. GEFFEN, and V. J. BERRY, JR., Stanolind Oil and Gas Co.

2:45 p.m. to 5:00 p.m. — PRODUCTION OPERATIONS — Roof Garden, Plaza Hotel

381-G: *Use of Potential Profiles to Evaluate Current Requirements for Control of Casing Corrosion,* by J. D. SUDBURY, J. E. LANDERS, and D. A. SHOCK, Continental Oil Co.

382-G: *Remote Automatic Control of Oil Production,* by C. R. BAYLESS and J. W. DAUGHTREY, Gulf Oil Corp.

383-G: *Where Corrosion Control Stands Today,* by H. L. BILHARTZ, Atlantic Refining Co.

6:30 p.m. to 10:30 p.m. — PETROLEUM BRANCH BARBECUE SUPPER and FRONTIER PARTY — McArthur Park, San Antonio

Tuesday, October 19

8:00 a.m. to 5:00 p.m. — REGISTRATION AND EXHIBITS — Ballroom, Plaza Hotel

9:00 a.m. to 11:15 a.m. — RESERVOIR MODEL STUDIES — Ballroom, Gunter Hotel

411-G: *The Encroachment of Injected Fluids beyond Normal Well Patterns,* by B. H. CAUDLE, R. A. ERICKSON, and R. L. SLOBOD, The Atlantic Refining Co.

412-G: *Performance of Water Drive Reservoirs, Including Pressure Maintenance, as Determined by the Reservoir Analyzer,* by JAMES M. MCDOWELL, Gulf Research and Development Co.

413-G: *Oil Recovery Performance of Pattern Gas or Water Injection Operations from Model Tests,* by F. F. CRAIG, JR., T. M. GEFFEN, and R. A. MORSE, Stanolind Oil and Gas Co.

9:00 a.m. to 11:15 a.m. — ECONOMICS AND MANAGEMENT — Aztec Theater

420-G: *The Economics of the International Petroleum Industry*, by A. H. CHAPMAN and JAMES TERRY DUCE, Arabian-American Oil Co.

421-G: *Legal Aspects of Offshore Oil Operations*, by Comdr. EMORY CLARK SMITH, Naval Petroleum Reserves.

422-G: (Not yet selected)

9:00 a.m. to 11:30 a.m. — PRODUCTION OPERATIONS — Roof Garden, Plaza Hotel

384-G: *Studies of the Mechanism of Paraffin Deposition and Its Control*, by D. A. SHOCK, J. J. CROCKETT, and J. D. SUDBURY, Continental Oil Co.

385-G: *Big Mineral Field Exploitation — A Challenge to Engineers*, by J. M. GARLICK, Shell Oil Co.

386-G: *A Low Cost Method of Production Stimulation*, by A. W. GARST, Stanolind Oil and Gas Co.

12:00 m. — PETROLEUM BRANCH MEMBERSHIP LUNCHEON — Ballroom, Gunter Hotel, John R. McMillan, Petroleum Branch Chairman, Presiding

12:00 m. — For the Ladies — LUNCHEON and STYLE SHOW — Menger Hotel

2:45 p.m. to 5:00 p.m. — RESERVOIR MODEL STUDIES — Ballroom, Gunter Hotel

414-G: *Estimated Effect of Horizontal Fractures on Production Capacity*, by PAUL B. CRAWFORD and BOBBY L. LANDRUM, Texas Petroleum Research Committee.

415-G: *Scaling Laws for Use in Design and Operation of Water-Oil Flow Models*, by L. A. RAPOPORT, Carter Oil Co.

416-G: *Displacement of Oil from Porous Media by Miscible Liquids*, by J. OFFERINGA and C. CAN DER POEL, Koninklijke/Shell Laboratorium, Amsterdam.

2:45 p.m. to 5:00 p.m. — PRODUCTION EQUIPMENT Roof Garden, Plaza Hotel

394-G: *Producing Lease Operations — Design of Operating and Maintenance Jobs and Related Tools and Transportation Equipment*, by HAROLD S. KELLY and ROGERS FILSON, Phillips Petroleum Co.

395-G: *Radio Communications in the Petroleum Industry*, by JERRY S. STOVER, Communications Engineering Co.

396-G: *Theoretical and Practical Aspects of Free Piston Operation*, by J. M. LEBEAUX and L. F. SUDDUTH, Stanolind Oil and Gas Co.

397-G: *A New Tool for Perforating Casing Below Tubing*, by B. M. CALDWELL and H. D. OWEN, Welex Jet Services, Inc.

7:00 p.m. to 12:00 m. — PETROLEUM BRANCH BANQUET AND DANCE — Club Seven Oaks, North San Antonio

Wednesday, October 20

8:00 a.m. to 5:00 p.m. — REGISTRATION and EXHIBITS — Ballroom, Plaza Hotel

8:30 a.m. to 11:15 a.m. — FORMATION FRACTURING — Aztec Theater

404-G: *Optimum Sand Concentrations in Well-Treatments*, by PETER DEHLINGER, Continental Oil Co., W. H. BROWNE, Battelle Memorial Institute, and C. O. BUNDRANT, The Western Co.

405-G: *The Development and Application of "Frac" Treatments in the Permian Basin*, by J. M. MOORE and D. E. RAMSEY, Dowell, Inc.

406-G: *Fracturing at High Injection Rates Spraberry Trend Area Field*, by T. P. BROOKS, P. C. O'QUINN, and W. E. LIFE, Southern Production Co., Inc.

407-G: *Effects of Extensive Well Fracturing on the Water Flood Operation in North Texas Strawn Sand*, by GENE E. ROARK and J. D. LINDNER, James A. Lewis Engineering, Inc.

9:00 a.m. to 12:00 m. — DRILLING and WELL COMPLETION — Ballroom, Gunter Hotel

387-G: *Tubing Joint Leakage*, by MARTIN E. TRUE, Humble Oil and Refining Co.

388-G: *Field Welding on Oil Field Tubular Goods*, by J. N. BIRON and B. G. FRAZIER, Gulf Oil Corp.

389-G: *A Proven Method for the Control of Incompetent Sand Formations*, by H. B. RITCH, Dowell, Inc.

390-G: *Strength of Oil Well Cements and Additives Under High Temperature Well Conditions*, by CALVIN D. SAUNDERS and WAYNE A. WALKER, Halliburton Oil Well Cementing Co.

9:00 a.m. to 11:15 a.m. — GEOLOGICAL ENGINEERING — Roof Garden, Plaza Hotel

398-G: *Application of Radioisotopes to Sub-Surface Surveys*, by A. A. ALBERTS, R. D. COCANOWER, and C. O. BUNDRANT, The Western Co.

399-G: *Use of Spectrographic Analysis for Correlation in Limestone Rocks*, by JOHN C. MILLER and FRANK W. JESSEN, The University of Texas.

1:30 p.m. to 4:30 p.m. — DRILLING — Ballroom, Gunter Hotel

391-G: *Performance Data and Description of New Type Drilling Mud D-Gasser*, by R. W. ERWIN and R. L. O'SHIELDS, Salt Water Control, Inc.

392-G: *The Pumpability of Clay-Water Drilling Fluids*, by I. HAVENAAR, Koninklijke/Shell Laboratorium, Amsterdam.

393-G: *Lignosulfonate Stabilized Emulsions in Oil Well Drilling Fluids*, by W. C. BROWNING, Marathon Corp.

2:00 p.m. to 4:00 p.m. — RESERVOIR ENGINEERING — Roof Garden, Plaza Hotel

417-G: *Production of Water-Driven Reservoirs Below Their Bubble Point*, by A. B. DYES, The Atlantic Refining Co.

418-G: *Advantage of a Coordinated Formation Evaluation Program*, by H. M. SHEARIN, JR. and J. R. LATIMER, Humble Oil and Refining Co.

419-G: *Multiple Correlation Techniques in Petroleum Engineering*, by R. K. GUTHRIE and MARTIN H. GREENBERGER, Seeligson Engineering Committee. ★★★

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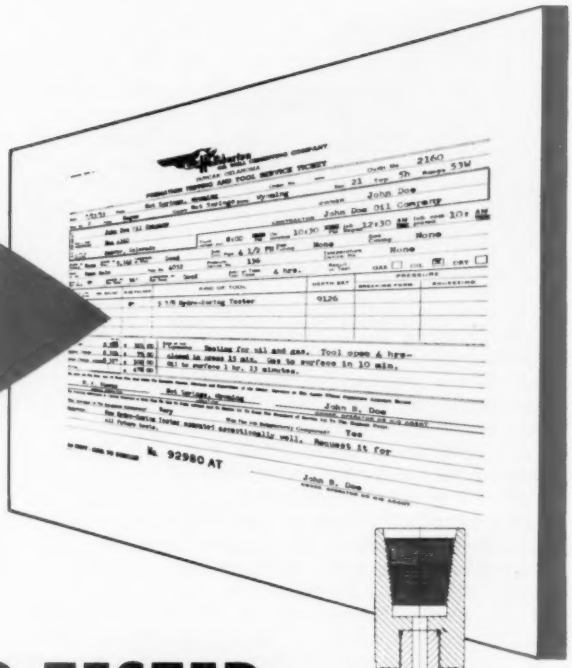

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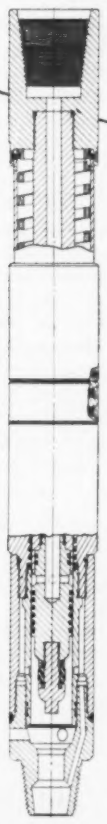

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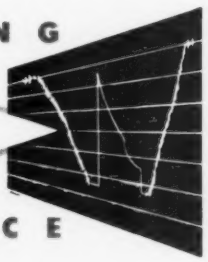

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H. T. OLSEN has opened an office in Los Angeles as a consulting petroleum engineer specializing in the valuation of oil and gas properties and in property management. He is also California consultant to San Juan Oil Co. of Dallas. Prior to opening his California office, Olsen worked with Superior Oil Co. from 1937 until 1952. Then he opened a petroleum consulting office in Dallas, which he operated until February, 1954.

☆

ROBERT S. MOEHLMAN was recently elected executive vice-president and C. WARDELL LEISK was elected vice-president of the Austral Oil Exploration Co., Inc. Moehlman has been with the company since its formation in 1950, having worked as chief geologist for South American Mines Co. prior to this. Leisk joined the company in 1952 after working with The Texas Co., Hendrickson Oil Co., and with George W. Strake, Houston independent oil operator.

☆

RAYMOND T. LAIRD has opened an office in Oxnard, Calif., as a consulting petroleum geologist. Formerly he was developmental geologist with Standard Oil of California in Los Angeles.

☆

LOUIS F. DAVIS and T. C. FRICK will assume new positions in the Atlantic Refining Co. organization in the near future. Davis has been named assistant manager of the Oklahoma-Kansas region, with offices in Tulsa. He has been general production superintendent since 1951. Frick has been appointed manager of the Production Division and will office in Dallas. He has been regional coordinating manager of the Southwest Texas region at Corpus Christi.

☆

M. M. LEIGHTON has retired from his position as chief of the State Geological Survey of Illinois after serving 31 years as chief and 35 years as geologist. His successor is John C. Frye, State geologist and executive director of the Kansas Geological Survey, and professor of geology at the University of Kansas.

☆

S. F. BIRD, chief reservoir engineer for Amerada for the past seven years, has resigned to accept a position as petroleum engineer with Herman H. Kaveler, petroleum consultant in Tulsa. The University of Oklahoma graduate has worked with International Petroleum Co. in Peru and with Imperial Oil Co. in western Canada, in addition to his experience with Amerada.

☆

FRANKLIN ALTON WADE has accepted the position of professor and head of the Department of Geology at Texas Tech College, Lubbock. Formerly he was professor of geology at Miami University, Oxford, Ohio.

☆

R. J. GRANBERRY has been elected to the board of directors of Core Laboratories, Inc. The graduate of Louisiana State University has been employed by Core Lab since 1941. He will continue as district engineer for the company's entire Lower Texas Gulf Coast and South Texas operations, the position he has held since 1947.

R. V. SMITH is now technical advisor to the chief production engineer of the Natural Gas Department, Phillips Petroleum Co. Formerly he was natural gas engineer with the Bureau of Mines, Bartlesville.

☆

J. H. GALLOWAY and L. H. BYRD have been promoted in the Humble Oil & Refining Company's Production Department. Galloway, formerly assistant superintendent of the West Texas Division, has been named assistant manager of the Production Department to assist in handling field assignments. Byrd, production superintendent in Humble's California area, will succeed Galloway in the Midland post. Other Humble changes include the moving of J. C. MCDUFFIE, JR., to Thompsons, Gulf Coast Division, as district petroleum engineer, and of W. B. SWAN to the Houston office as senior petroleum engineer.

☆

LOUIS C. BALL has been named vice-president and assistant to the president of Johnston Testers, Inc. He formerly was regional manager of Rheem Manufacturing Co. in Houston and has worked with Henry J. Kaiser and the Aluminum Co. of America.

☆

ERNEST SLAUGHTER, JR., has been appointed manager of the Wichita Falls District by Lufkin Foundry & Machine Co. The Texas A&M graduate has worked with the company in Lufkin and Odessa, Texas.

☆

S. K. MOREDOCK, JR., has accepted the position of president of a newly-formed royalty corporation known as Texas Minerals, Inc., located in Houston. Prior to taking this position, he was valuation engineer with the U. S. Treasury Department, Bureau of Internal Revenue, Oklahoma City, Okla.

Panhandle, Hobbs, and Hugoton

GROWTH of BRANCH CONTINUES as THREE NEW SECTIONS APPROVED

Jack Phillippe

The Petroleum Branch continued its rapid growth as three new Sections, predominantly petroleum in membership, were recently approved by the AIME Board of Directors. They are the Panhandle Local Section, which meets in Pampa, Tex., the Hugoton Local Section, which meets in Liberal, Kan., and Guymon, Okla., and the Hobbs Petroleum Section, which meets in Hobbs, N. Mex.

These sections were formed pending release of the territory they cover from the Section which formerly held the counties concerned. The Hobbs Section was designated as a "Petroleum" Section because it overlays another Section, and the Panhandle and Hugoton groups are regular local sections.

Panhandle Local Section

With Donald E. Radtke, of Magnolia Petroleum Co., as chairman, the Panhandle Section has increased in membership by 85 per cent since its recent organization. The Section embraces the Texas counties of Hutchison, Roberts, Hemphill, Oldham, Potter, Carson, Gray, Wheeler, Deaf Smith, Randall, Armstrong, Donley, Collingsworth, Parmer, Castro, Swisher, Hall, Briscoe, and Childress. All of these counties formerly were in the territory of the Oklahoma City Section.

Other officers of the Panhandle Section are Joe M. Daniels, The Texas Co., first vice-chairman; Jack C. Bendler, Phillips Petroleum Co., second vice-chairman; and Henry J. Rose, Cabot Carbon Co., secretary. Directors are T. S. Whitis, Amarillo Oil Co., D. W. Jackson, Gulf Oil Corp., and J. H. Ziser, Phillips Petroleum Co.

Participating in a discussion at the June meeting of the Panhandle Local Section are, seated left to right: Don W. Jackson, Gulf Oil Corp., director; Henry J. Rose, Cabot Carbon, secretary-treasurer; and John Arps, British-American, the speaker. Standing are Donald E. Radtke, Magnolia, chairman; J. A. Ziser, Phillips, director; and Jack C. Bendler, Phillips, second vice-chairman.

Hugoton Local Section

The Tri-State Gas and Oil Assn. voted in February to petition for AIME local section status and has fulfilled the requirements. Jack Phillippe, Panhandle Eastern Pipe Line Co., is the chairman of the Hugoton Local Section which includes counties in four states. Other officers are W. L. Horton, vice-chairman, and C. P. Pycatte, secretary-treasurer.

Texas counties included in the Section are Hansford, Lipscomb, Dallam, Sherman, Ochiltree, Hartley, and Moore. Oklahoma counties are Cimarron, Texas, Beaver, and Harper. Colorado counties are Prowers and Baca. Kansas counties are Stevens, Seward, Meade, Clark, Ford, Gray, Haskell, Grant, Stanton, Hamilton, Kearny, Finney, Scott, Wichita, and Greeley.

Hobbs Petroleum Section

The organizational meeting of the Hobbs Petroleum Section attracted 102 persons, the majority of whom were non-members of the AIME interested in membership. W. G. Abbott, Amerada Petroleum Corp., was elected chairman, and John Yuronka, Jr., was elected secretary, after the group voted unanimously to petition for Section status.

The Hobbs Petroleum Section "overlays" the Carlsbad and Potash Section and includes the New Mexico counties of Lea, Eddy, Chaves, and Roosevelt, and the Texas counties of Gaines and Yoakum. Some of these counties had previously been the territory of the South Plains and Permian Basin Local Sections.

The formation of new local sections in areas where sufficient numbers express an interest in organizing such a group is a part of the continual program of the Petroleum Branch to "take the Institute to its members." ★★★

Harold Decker, center, discusses AIME activities with two new officers of the Hobbs Petroleum Section. They are W. G. Abbot, chairman, left, and John Yuronka, Jr., secretary.

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by AL CAPP
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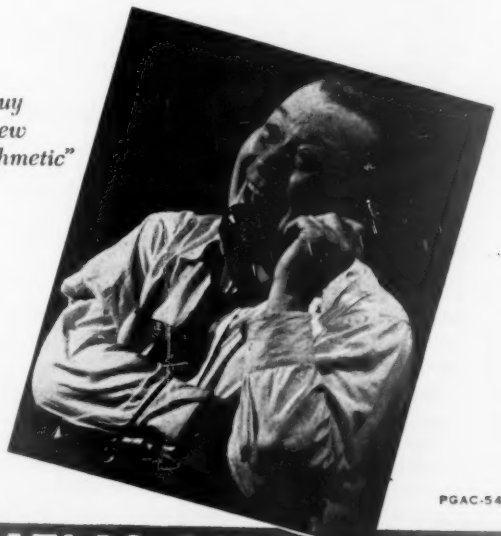

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NOMINEES for AIME OFFICES for 1956

Carl E. Reistle, Jr., of Humble Oil & Refining Co., has been nominated for AIME president for 1956. Biographical sketches of Reistle and of the other nominees for vice-president and director and for director are published here in compliance with Article IX, Section 1, of the Institute by-laws.

These men were nominated by the Institute Nominating Committee, each to serve a three-year term with the exception of the president. If no other nominations are received by Sept. 1, 1954, these nominees will be declared elected. The Institute by-laws state "... If any complete or partial ticket of nominees signed by 25 Members or Associate Members is transmitted to the Secretary of the Institute prior to September first, a letter ballot as hereinafter provided shall be printed and mailed before October first to the membership in the United States, Canada, and Mexico."

For President

C. E. REISTLE, JR., is a member of the Board of Directors of Humble Oil & Refining Co. and in charge of the Production Department. After graduation from the University of Oklahoma in 1922 with a BS degree in chemical engineering, he joined the U. S. Bureau of Mines in Bartlesville as a junior petroleum chemist. In 1933 Reistle became chairman of the East Texas Engineering Assn., a cooperative organization formed to obtain engineering facts on the efficient operation of the East Texas field. He joined Humble in 1936 as engineer-in-charge of the Petroleum Engineering Division and rapidly succeeded to head of the Division, general superintendent of the Production Department, and then to manager of production operations. In 1948 Reistle assumed his present position, after serving in World War II as technical advisor for District III of the Petroleum Administration for War.

For Vice-President and Director

WALTER A. DEAN is Cleveland works chief metallurgist of the Aluminum Co. of America. He is a 1926 graduate in chemical engineering of Cooper Union Institute of Technology in New York City and received his MS and PhD degrees from Rensselaer Polytechnic Institute. Following his graduation, he joined the Aluminum Co. of America to work in the research laboratories. In 1945 he was named assistant manager of the permanent mold plant at Cleveland, and in 1949 he assumed his present position.

WILLIAM WALLACE MEIN, JR., is president of Calaveras Cement Co., Bishop Oil Co., and Clear Lake Water Co., all of San Francisco. He is a 1932 graduate of Harvard College with an AB degree in engineering sciences and worked first for the Calaveras Cement Co. plant at San Andreas, Calif. Then he spent two years as petroleum production engineer and oil geologist for Bishop Oil Co. in Texas and Oklahoma. Resuming his employment with Calaveras, he advanced to the vice-presidency and in April, 1951, to the presidency. In 1947 he was elected president of Clear Lake Water Co. and in 1953 became president of Bishop Oil Co.

For Director

RICHARD WHITSETT FRENCH, JR., is vice-president of production for the Standard Oil Co. (Ohio). He attended the Universities of Delaware, Southern California, and Harvard. In 1933, after a service tour and some experience with General Electric Co., he joined the Continental Oil Co., of Ventura, California. By 1936 he had become production engineer for the Los Angeles office, and after serving for seven years in this capacity was moved to Ponca City as assistant manager of the Production Department. In 1947 French accepted the position of chief engineer and assistant to the vice-president in charge of production. He continued to move up rapidly and assumed his present position in April of 1954.

D. C. HELMS has been associated with the Lehigh Navigation Coal Co. since 1909. Prior to that he had worked with the Brooklyn Navy Yard, American Bridge Co., St. Clair Coal Co., and Philadelphia & Reading Coal & Iron Co. His first position with Lehigh was as a chairman and draftsman. Prior to his retirement, he had become vice-president and served in that capacity for two years.

ALVIN J. HERZIG was recently elected vice-president in charge of research for Climax Molybdenum Co. The University of Michigan graduate worked for National Supply Co., Toledo, before returning to the University to obtain his MSE degree in 1931. Then he joined the staff of Climax Molybdenum Co. of Michigan in 1949.

HOWARD C. PYLE has been president of Monterey Oil Co. since November, 1951. He holds a BS degree from the University of California and a MS degree from USC. He worked in the oil fields of California and Venezuela before compiling an outstanding record in World War II as a member of the staffs of General Eisenhower and Field Marshall Montgomery, and as deputy chief of G-4 petroleum branch, communications zone. Before accepting his present position, he was, in turn, vice-president of the Bank of America, president of Continental Consolidated Corp. and Continental Corp., and a consulting petroleum engineer in Los Angeles.

E. H. ROSE was until recently research engineer for Tennessee Coal & Iron Division of U. S. Steel Corp. The University of Kansas graduate began his career in Bolivia as a mill superintendent with the Patino Mines, moved to Mexico in a similar capacity, and to Canada in 1930. Until 1945 he was mill superintendent of International Nickel Co. of Canada. He has been a member of the raw materials advisory committee, U. S. Atomic Energy Commission since 1949.

JOHN W. VANDERWILT is president of the Colorado School of Mines, Golden. The graduate of the University of Michigan and Harvard Graduate School has instructed in geology at the University of Colorado and served as a junior geologist with the U. S. Geological Survey in Washington, D. C. In 1950 he was named to his present position, after returning to the School of Mines as a trustee in 1947. In 1953 he became a member of the Committee on Mineral Research, National Science Foundation. ★★★

Employment Notices

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 800 Fidelity Union Bldg., Dallas 1.

Replies to positions coded W137 and Y9664 below should be addressed to: Engineering Societies Personnel Service, 8 West 40th St., New York 18, N. Y. The ESPS, on whose behalf these notices are published here, collects a fee from applicants actually placed.

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☆Petroleum Production, Geological and Engineering Clerk, experienced in keeping field records, tabulating data and typing reports. Salary, $3,900-$5,200 a year. Headquarters, New York, N. Y. Y9664.

☆Teacher for Petroleum Engineering subjects, preferably with master's degree. One-half time to be devoted to teaching and the remainder of the time can be spent on work towards advanced degree in science, engineering, or mathematics. Salary, $3,600 for approximately nine months. Send complete record to Department of Mining and Petroleum Engineering, The Ohio State University, Columbus 10, Ohio.

☆Industrial fellowships and state sponsored research positions available. If interested and qualified with BS or equivalent in petroleum engineering, send resume of education and experience to Graduate Advisor, Department of Petroleum Engineering, University of Texas, Austin 12, Tex.

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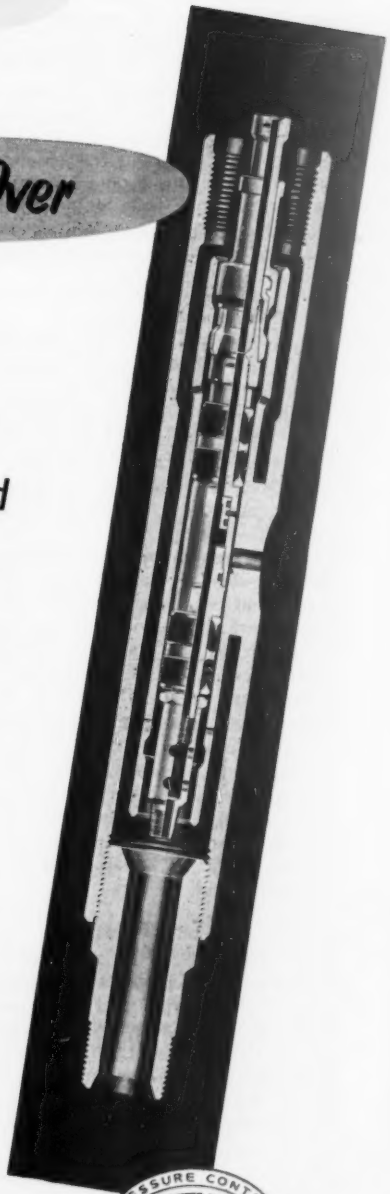

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Talks, Demonstration on In-Situ Combustion Draw Record Attendance to Pacific Junior Group Meet

By DAVID K. HAYWARD

Attendance records were broken again when 165 members and guests of the AIME Junior Group of the Pacific Petroleum Chapter met at the Turf Club in Rivera to hear Jan Law and Charles Wright speak on the subject of "in-situ combustion." During their presentations, Paul Culligan conducted an actual laboratory "burn" of a typical California oil sand.

Wright, president of Oilwell Research, described in-situ combustion as a means of applying heat to a reservoir to reduce the oil viscosity and to strip the sand of its oil. The process is one of first adding heat to the reservoir and then conducting a hot air drive. After initial heating with a bottom hole heater, subsequent heating is obtained from the residual coke beds in the reservoir which are kept aglow by air injection. Liquids recovered may amount to 75-90 per cent.

Two Schools of Thought

Since the year 1920, when Standard Oil Co. of New Jersey applied for the first patent on distilling crude oil underground, developments have led up to successful field tests in the mid-continent by Sinclair and Magnolia. Recently, General Petroleum Corp. announced its proposed test in the South Belridge field of California. There are two schools of thought; Sinclair uses a bottom hole gas burner and obtains a complete high temperature front, volatilizing all hydrocarbons, and Magnolia uses an electric heater, and elevates the temperature only enough to reduce the viscosity to a desired level.

Problems ahead are: (1) the economics of individual projects, (2) how to increase the petrochemicals, (3) means of increasing the Btu content of produced gases, and (4) how to apply the best method in a particular sand.

Typical Data

Jan Law, petroleum engineering consultant, presented some typical data on the operation of an in-situ combustion field experiment. Besides the procurement and maintenance of equipment, energy must be provided to heat the reservoir and to compress the injected air. It may take about 27,000 Btu/cu ft of oil sand to elevate the temperature to 600°F initially, but from then on the residual coke beds can supply sufficient heat to continue the operation. Compression costs, however, are the bottleneck. For example, consider a 5-acre five-spot injection pattern. For each foot of vertical sand section in each injection well, it would require ultimately 150 MCF/day of compressed air for injection. A 100-ft sand would require compressor capacity of 15,000 MCF/day per injection well. On the other hand, a 1-acre five-spot pattern would require ultimately 70 MCF/day per foot, or 7,000 MCF/day for a 100-ft sand. Obviously, then, a balance must be found between well spacing, drilling costs, and sand thickness.

Laboratory Experiments

Wright returned to the rostrum to report on the results of his laboratory experiments. He has obtained gravity rises of 1.2 to 3.0° API. Heating of the oil sand partially segregates the components of crude oil so that less residual matter need be sent to the refinery. Furthermore, certain petrochemicals estimated to be worth $50/bbl can be obtained from producing wells.

During a question period, Norris Johnston, president of Petroleum Technologists, asked if by-passing of injected air has been a particular problem.

No By-Passing Problem

Law answered him by recalling Sinclair's field experiment in which cores were taken following the burn, indicating complete recovery from the entire 51-ft sand section. Since there was permeability variation in the sand, by-passing would have been anticipated in a conventional gas drive or water drive, but by-passing did not reduce recovery in the Sinclair test. At high temperatures, perhaps the process is more of a gas-vapor drive than a gas-liquid drive, therefore affording more efficient recovery.

Paul Culligan, director of the Oilwell Research laboratory, conducted a laboratory burn during the meeting. Shown were the oil sand prior to burning, the progress of the combustion front moving through the Pyrex tube, the glow of the residual coke left behind, the oil driven from the tube, and the clean, white sand which remained.

Reinartz Recovering from Injury Sustained in Fall At Meeting in New York

AIME President Leo Reinartz had the misfortune to fall while attending a session at the meeting of the American Iron and Steel Institute in the Waldorf Astoria Hotel in New York on May 26. He severely injured the tendon and muscles in his right leg, just above the kneecap. His leg was operated on two days later and he was confined to the New York hospital for several weeks afterward. He flew back to Middletown, Ohio, last month, but does not expect to get about normally before September.

Clay Mineral Technology Theme of Houston Meeting

"Clay Mineral Technology" is the theme of the Third National Clay Minerals Conference to be held at the Rice Institute, Houston, Oct. 27, 28, 29, 1954. The Conference is sponsored by the Clay Minerals Committee of the National Research Council.

A special part of the program will be devoted to fundamental or applied papers. Anyone interested in presenting papers in any of these or other fields pertaining to clays or related minerals has been invited to contact A. F. Frederickson, Washington University, St. Louis 5, Mo.

Company Offers Fellowship At University of Texas

A $1,500 fellowship at the University of Texas is being offered again this year by Lane-Wells Co. The holder of the fellowship will be a candidate for the degree of Master of Science in petroleum engineering.

The appointment to the fellowship will be based upon scholarship and qualifications for research. Applications should include an official transcript of all college work, a photograph, a statement of marital status, experience record, and three references. Applications should be sent to H. H. Power, Department of Petroleum Engineering, University of Texas, Austin, Tex.

James O. Lewis Dies

James O. Lewis, 1946 recipient of the Anthony F. Lucas Medal, died at 8:35 a.m. on June 15. An appreciation of the Houston consultant who contributed so much to the industry will be carried in a future issue of PETROLEUM TECHNOLOGY.

ESTIMATING OIL RESERVES

J. J. ARPS
MEMBER AIME

THE BRITISH-AMERICAN OIL PRODUCING CO.
DALLAS, TEX.

This is a report of a talk given in June to the new Panhandle Local Section at Pampa, Tex. J. J. Arps, assistant to the executive vice-president and manager of the Research and Economics Department of British-American, has spoken on this subject before local sections in Tulsa, Dallas, Fort Worth, Wichita Falls, Lubbock, Odessa, Denver, and Casper, and before Canadian technical groups in Calgary and Edmonton.

Estimating oil reserves is one of the most important phases of the work of a petroleum engineer, since most technical problems are based on a recommendation comparing the cost in terms of dollars with the result in terms of barrels. On such estimates may depend:

a. The price to be paid in case of a sale or purchase of an oil property;

b. The proper depreciation rate for the investment in oil properties;

c. The division of ownership in unitization;

d. Large-scale plans for development or construction of auxiliary plants;

e. The construction of gasoline plants, pipelines, refineries.

Unfortunately, the answers are most urgently needed when only a minimum amount of information is available, while the interest in reserve figures — aside from their use for accounting purposes — usually declines when the property gets closer to its economic limit. At such time the estimates are known with much greater degree of accuracy.

The usual history of reserve estimates over the life of a property is illustrated with a hypothetical case, graphically shown as Fig. 1.

Three Periods

Three distinct periods are distinguished. The first one is the so-called "barrels per acre" period when the estimates are based on the performance of similar fields in the same area. This is the period before the first well is drilled. Estimates during this period could range from as low as AB (property not commercially productive) to as high as CD.

The second period is the "barrels per acre-foot" period when the estimates can be made on a volumetric basis. At this time the sand and oil characteristics should be known, as well as the net pay volume, while some idea must be available of the type of reservoir mechanism expected. The range of reserve estimates during this second period has now narrowed down from as high as GH to as low as EF (assuming the property is commercially productive).

During the third period of the hypothetical case the volumetric estimate, the "barrels per acre-foot period," can be balanced against estimates based on performance data. This is therefore called the "decline curve" period.

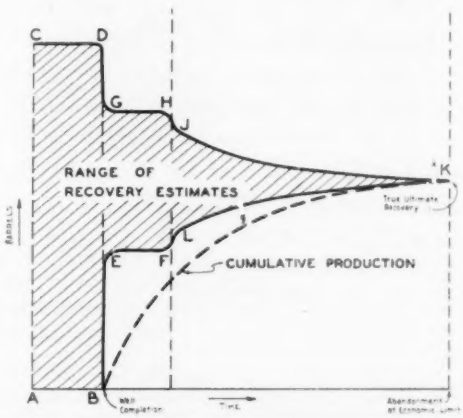
As the cumulative production increases (curve BK) during this third period, the range of estimates between JK and LK narrows itself down until at the time when the lease is ready for abandonment the maximum and minimum estimates converge in point K and the estimate becomes a certainty.

Under-estimating — Over-estimating

In looking over the history of recovery estimates over a period of time in many different fields, it seems to be a common experience that really good properties, such as in the East Texas, Yates or Oklahoma City fields, have been generally under-estimated in the beginning, and that the poorer ones such as in the Spraberry or West Edmond fields are usually over-estimated during the early stages.

The methods followed during the second, or "barrels per acre-foot" period, when estimates are made on a volumetric basis, was first discussed. The type of calculations that must be made to arrive at minimum and maximum estimates for solution gas drive and water drive fields was shown. A new method of estimating the ultimate recovery for solution gas drive type fields using the free gas space created at abandonment time to

(Continued on Page 57)



PERIOD→	I	II	III
TYPE OF DATA	COMPARATIVE DATA	VOLUMETRIC DATA	PERFORMANCE DATA
	From similar fields in barrels per acre	Subsurface, Electric logs, Core analysis, BHS analysis	WITH WATER DRIVE MECHANISM: Production rate decline data (in prorated fields potential test data); Oil percentage data; Rise in water table data. WITH DEPLETION OR GAS DRIVE MECHANISM: Production rate decline data (in prorated fields potential test data); Gas oil ratio data; Pressure and material balance data

Fig. 1 — Schematic representation of the three periods in the life of a producing property, the type of data used for and the range of the recovery estimates.

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Allocation of Costs

(Continued from Page 13)

Because it depends on the use of gas-well gas costs from a representative number of gas wells to determine casinghead gas unit costs, the application of the energy content method discussed here is not adaptable to companies that have little or no gas-well gas production. It is felt, however, that other modifications of the basic principle involved in the energy content method can be devised to overcome this limitation.

Conclusion

It is recognized that the method outlined herein for allocating the common costs incurred by petroleum producers in supplying liquids and gases is not a complete answer to the problem. The need for allocating these costs has come only recently and methods of making the allocation are in the early stages of development. As gas continues to grow in importance, proper cost allocation will become increasingly important. As more and more operators in the industry find it necessary to make allocations, improvements in methods will come. The important thing is that we recognize the fact that an appreciable portion of the industry's costs are attributable to gas and begin to make an effort to determine what that portion is. The method used at Humble is, we hope, at least a start in the right direction.

★★★

Oil Reserves

(Continued from Page 55)

compute the unit recovery was described. This method is based on a relationship between this free gas space, the type of oil, the solution gas-oil ratio, and the type of rock, and was demonstrated with a series of curves.

Comparisons Made

In the presentation, comparisons were then made of solution gas drive recoveries between sandstones and limestones, and for sandstone reservoirs encountered at different depths.

While discussing the third period, or "decline curve" period, it was stressed that estimates based on performance data do not have to be confined to production decline curves alone. Other variables which are being measured with reasonable accuracy and which have a known end point can be plotted against either time or cumulative and can be extrapolated to this end point to provide the desired answer.

Examples were shown in which percent oil in total fluid, cumulative gas production, changing water table, etc., are used to arrive at the remaining reserves.

A classification of production decline curves in three groups consisting of constant percentage, hyperbolic and harmonic decline was shown, and the formulas for the rate-time and rate-cumulative relationships for each of those cases was developed.

Rules-of-Thumb

It was then shown how the rate-time and rate-cumulative curves for each of those cases can be straightened out by using different kinds of graph paper. Illustrations were given of actual examples of different types of decline curves and their extrapolation.

The meeting ended with a presentation of a collection of "rules-of-thumb" covering simplified calculation methods pertaining to petroleum engineering problems.

Board of Directors Approves Changes In By-laws and Nominating Procedure

A revision in the Institute by-laws and certain changes in the nominating procedure for AIME officers and directors were approved by the AIME Board of Directors at its recent meeting.

The revision in Art. XI, Sec. 3, of the AIME by-laws, published in the April issue of all three Institute journals, was passed by the Board. In short, the amendment removes the limitation of $400 as the maximum grant to a Local Section in any year.

The aid given to Local Sections who request it in 1954 consists of 50 cents per member on Jan. 1, 1954, half of the initiation fee received from all new members, and the first-class railroad fare to and from the Annual Meeting for the Section Delegate. Aid to be granted in 1955 has not yet been decided upon in any of these three respects.

The principal change made by the Board in the nominating procedure for Institute officers is that a two-thirds majority, instead of a simple majority, is necessary for selection of the candidates by the Nominating Committee. Briefly, the change is as follows:

Twelve votes out of the 18 are required to name a candidate for the slate, the chairman having a vote. If no candidate receives 12 or more votes at the meeting of the Committee, a letter ballot or ballots shall be conducted among the members of the Committee within a 60-day period. If the letter ballots fail to provide nine candidates each with 12 or more votes, then the two highest candidates shall be submitted to all members of the Institute for letter ballot.

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Proposed for Membership, Petroleum Branch

TOTAL AIME membership on Apr. 30, 1954, was 20,519; in addition 1,401 Student Associates were enrolled.

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The Institute desires to extend its privileges to every person to whom it can be of service, but does not desire as members persons who are unqualified. Institute members are urged to review this list as soon as possible and immediately to inform the Secretary's office if names of people are found who are known to be unqualified for AIME membership.

In the following list C/S means change of status; R, reinstatement; M, Member; J, Junior Member, A, Associate Member; S, Student Associate.

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California
Fullerton — West, William Junius (M).
Maywood — Aker, Jimmie Rollen (R, C/S-S-A).

Colorado
Denver — Hanson, Carl Dwayne (R, M).
Englewood — Kunzman, William Joseph (J).

Kansas
Great Bend — Parks, Robert Winfield (J).
Pratt — Gibbs, James Brice (M).

Louisiana
Lake Charles — Hillhouse, Gordon Emerson (M).

New Mexico
Hobbs — Harrison, Edward Tate (M); Maddox, Jack F. (M).
Jal — Cole, Charles Monroe, Jr. (J).
Maljamar — Davis, Russell Judy, III (J).

Oklahoma
Avant — Hobson, J. C., Jr. (J).
Chickasha — Fitzgerald, Daniel Edward (J).
Duncan — Causey, Norman Henry, Jr. (M); Saunders, Calvin Duane (M).
Oklahoma City — Donahoe, Charles William (J); Ernst, Edward August (A); Taylor, Burrell Gale (J); Zimmerman, Grier Dudley (J).
Pauls Valley — Campbell, Arnold Ernest (A).
Tulsa — Blevans, Don W. (M); Dunn, George Vincent, Jr. (J); Gardner, Frank Johnson (M); McGhee, Edwin (M).

Texas
Alice — McNeill, Hubert Earnest (A).
Alvin — Milner, Charles Porter (J).
Amarillo — Lauth, Robert Edward (J); Osgood, Charles Edwin, Jr. (J).
Arlington — Bradley, Howard Bishop (C/S-A-M).
Austin — Keithly, Clyde Marion (M).
Ballinger — Perdue, Howard Mullins (J).
Breckenridge — Sutton, Cecil Calvin (M).
Corpus Christi — Freeze, Burlin E. (M); Watts, Claud Arliss (J).
Dallas — Ford, Walter Othello, Jr. (J); Heald, Benj. Carter (A); Teubner, Wilbur Glenn (M); Thomas, Clifford Eldon, Jr. (J); Wiederkehr, Alvin Maurice (M); Williams, Robert Guy (A).
Encino — Willingham, James Ernest (M).
Houston — Dawson, Lester Roy (M); Freeland, Jean (M); Logan, Robert Vincent (A); Pearce, Sam William (A); Reddie, William Andrew (M); Stone, Herbert Losson (J).
Levelland — Stacey, Carl Edward (M).
Odessa — Moriarty, Francis William (M).
Pampa — Graham, James William, Jr. (J).
San Antonio — Bommer, Cleon L. (J).
Snyder — McGannon, Richard Louis (J).
Tyler — Key, Homer William (J).

Wyoming
Casper — Jones, Harold Sinclair (M).
Riverton — Larson, Robert E. (R, C/S-A-M); Lear, Bert Allen (R, C/S-S-J).

Canada
Edson, Alta — Klein, Frans (M).

Egypt
Cairo — El Mekkawy, Abdel-Sattar Mohamed (R, C/S-S-J).

Italy
Fortunati, Federico (M).

Persian Gulf
Dukhan, Qatar — Wheatley, Peter Derek (J).

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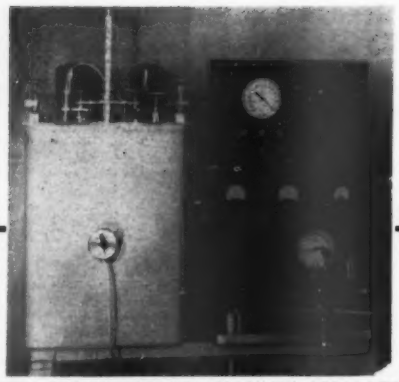

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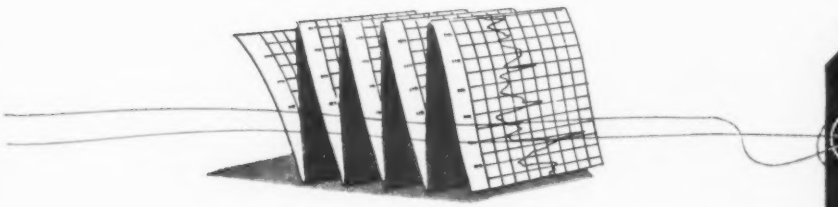

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